



# **Maritime electromagnetism and DRDC Signature Management research**

*Zahir A. Daya*

*Daniel L. Hutt*

*Troy C. Richards*

**Defence R&D Canada – Atlantic**

Technical Report

DRDC Atlantic TR 2005-278

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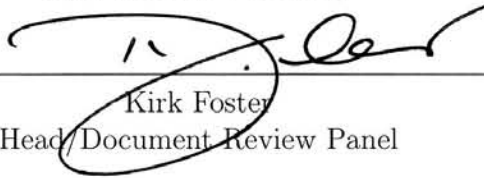
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## Abstract

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The broad field of electromagnetic activity in maritime environments is selectively reviewed from the perspective of scientific signature management. The physical origins and characteristics of naturally occurring electromagnetism *i.e.* ambient electromagnetic fields in the oceans are described. In particular, the sources or physical processes generating the fields, their magnitudes and the relevant time scales are noted. The ambient fields include the Earth's geomagnetic field, electromagnetic fields arising from the Earth-Ionosphere coupling and induced fields from oceanic flows. Localized electromagnetic signatures *i.e.* those emanating from naval platforms are reviewed. The signature strengths, their spatial and temporal extent, their origin and the representative physical models are discussed. Platform signatures include electromagnetic effects stemming from corrosion, permanent and induced magnetization of ferromagnetic components, and electromagnetic fields propagating from coastal settlements. Magnetic and electric signature management principles such as degaussing and active shaft grounding, respectively, are described. Defence Research and Development Canada (DRDC) contributions and present-day competencies in electromagnetic signatures are discussed. Possible directions for DRDC electromagnetic signature management are suggested.

## Résumé

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On examine de façon sélective le vaste domaine de l'électromagnétisme en milieu marin du point de vue de la gestion scientifique des signatures. On décrit les origines et les caractéristiques physiques de l'électromagnétisme naturel c'est-à-dire des champs électromagnétiques ambiants dans les océans, et on s'attarde en particulier sur les sources ou les processus physiques à l'origine de ces champs, sur leur intensité et sur les échelles de temps pertinentes. Les champs ambiants comprennent le champ géomagnétique terrestre, les champs électromagnétiques produits par le couplage Terre-ionosphère, ainsi que les champs induits par les courants marins. On se penche sur les signatures électromagnétiques localisées c'est-à-dire celles produites par les plates-formes navales, et on examine l'intensité des signatures, leur importance spatiale et temporelle, leur origine et leurs modèles physiques représentatifs. Parmi les signatures émises par les plates-formes, on compte les effets électromagnétiques découlant de la corrosion, l'aimantation permanente et induite des éléments ferromagnétiques et les champs électromagnétiques se propageant depuis des zones habitées sur la côte. On décrit les principes de gestion des signatures magnétiques et électriques, comme la démagnétisation et la mise à la masse par système actif de l'arbre de propulsion, respectivement. On examine les contributions de Recherche et développement pour la défense Canada (RDDC) dans ce domaine ainsi que ses compétences actuelles en matière de signatures électromagnétiques. On propose des orientations possibles pour la gestion des signatures électromagnétiques par RDDC.



# Executive summary

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## Maritime electromagnetism and DRDC Signature Management research

Zahir A. Daya, Daniel L. Hutt, Troy C. Richards; DRDC Atlantic TR 2005-278; Defence R & D Canada - Atlantic; December 2005.

### Background

Magnetism has played a profound role in sea-faring activities for over a thousand years, electric phenomena for over a hundred years. Navigation became reliable with the magnetic compass and vessels aged better when protected from rusting were early manifestations of oceanic electromagnetism. Expediency of oceanic commerce, patrol of homeland and naval missions have, over the last 50 years, necessitated the control of electromagnetic fields of vessels and platforms *i.e.* their electric and magnetic signatures.

Naval and commercial oceanic craft are, primarily, of steel construction. Thus, they are magnetized and they corrode. Loosely, the vessels have magnetic and electric signatures in their vicinity. As a result, vessels can be detected, recognized and targeted by their electric and magnetic signatures. The perceived risk and potential loss, human and economic, have driven research and development (R&D) efforts to understand and manage the electromagnetic (EM) signatures of vessels. These studies have addressed passive and active signature reduction, corrosion prevention, detection and classification, and ambient fields.

### Principal results

Electric and magnetic fields in the maritime environment have several physical origins. In the absence of human-related activity, the electromagnetic fields that persist arise from large natural sources such as the Earth's core, the earth-ionosphere-upper atmosphere system and coherent oceanic flows. These ambient or background fields prevail on a planetary length scale and reflect temporal scales of the underlying physical sources.

The predominant ambient magnetic field is the Earth's geomagnetic field which on every-day time scales is very nearly constant. Fluctuations in the maritime magnetic field due to motional induction result in periodic variations stemming from the lunar and solar tides and from oceanic swells. Occasional bursts in magnetic activity are related to solar flares and electrical storms which excite resonances in the Earth-Ionosphere system. These Schumann resonances are propagated into the oceans and

readily observed. Very low frequency variations in the magnetic field arise from seismic and tectonic activity. Ambient electric fields in the oceans originate from motional induction and ionospheric activity. The former when driven by continental scale circulations lead to an almost constant electric field. The lunar tides, swells and seawater currents lead to periodic signals in the oceanic electric field. Electrical activity in the ionosphere and upper atmosphere such as lightning lead to intermittent signals in the electric field in the oceans.

The typical range in time scales of electric and magnetic ambient fields in the maritime environment is from almost stationary or DC to a few tens of cycles per second. The magnitude of the variations are typically  $O(1)$  nT for magnetic fields and  $O(1)$   $\mu\text{V}/\text{m}$  for electric fields.

Human activity in the marine environment leads to localized electromagnetic signatures through seafaring missions, offshore platforms and coastal settlements. The signatures are spatially localized in that they persist at levels above or comparable to the ambient fields only near the vessel or settlement and are indistinguishable from the background at longer distances.

Vessels, such as naval frigates and oceanic liners, have magnetic signatures due to the iron in their construction. The static magnetization of a typical frigate-sized vessel is about 10000 nT at beam depth. Signature reduction technologies such as deperming and degaussing can reduce this to about 1000 – 2000 nT. The hull and propulsion parts of vessels are made of different metals, setting up a corrosion cell with the seawater. The electric current due to corrosion drives an almost static electric and magnetic field. A vessel's propulsion leads to alternating electric fields at the shaft frequency and its harmonics. Human settlements are concentrations of electromagnetic activity. The predominant 50 or 60 Hz line frequency is propagated from a coastal settlement into the oceans. In the near field, the corrosion related electric field, the shaft frequency and human settlement electric fields have levels of  $O(1000)$   $\mu\text{V}/\text{m}$  and frequency range 1 – 1000 Hz.

Defence Research and Development Canada (DRDC) has an active program in underwater electromagnetic signatures and sensing. DRDC's program has, over the years, made significant contributions in these fields. For example, active shaft grounding (ASG) as a means to eliminate electric field signatures at shaft propulsion frequencies was developed at DRDC.

Today, DRDC competencies in maritime electromagnetism include computational modelling of vessels, simulations of vessel-mine encounters, physical scale experiments, detection, tracking, classification, ambient field characterization, air-borne magnetic ranging, degaussing optimization and signature management operational procedures.



## **Future directions**

The threat from multi-influence, “smart” mines is expected to continue to increase in the near future. Reliance of the mines on the various electric and magnetic signatures is likely to grow. R&D resources should continue to be dedicated to addressing this compelling threat. Reduction of EM signatures, determining the tolerable signature levels, and defining operational procedures and tactics are important activities in the near term. Predictive signature model development to guide future vessel construction is likely to be important in the mid to long term. Mine jamming technologies based on intelligence of mine logics need to be enhanced.

Organic or onboard signature measurement is another important goal of DRDC EM R&D. It is an enabling capability for a naval vessel to be able to gauge its own signatures and local ambient noise levels in theater. Real time optimization could then be implemented and assure that the platform was in a state of minimum risk. Such a future-looking capability, can only be realized, with a broad and sustained commitment.

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# Sommaire

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## Maritime electromagnetism and DRDC Signature Management research

Zahir A. Daya, Daniel L. Hutt, Troy C. Richards; DRDC Atlantic TR 2005-278; R & D pour la défense Canada - Atlantique; decembre 2005.

### Introduction

Depuis mille ans, le magnétisme a joué un rôle très important dans la vie des marins ; par contre, les phénomènes électriques n'ont de l'importance que depuis plus d'un siècle. L'avènement du compas magnétique a permis de naviguer de façon fiable et les vaisseaux vieillissaient mieux lorsqu'ils étaient protégés contre la rouille : ces deux éléments constituent les premières manifestations de l'électromagnétisme en milieu océanique. La célérité du commerce maritime, la surveillance du territoire national et les missions navales ont nécessité le contrôle des champs électromagnétiques se propageant à partir des vaisseaux et des plates-formes, c'est-à-dire de leurs signatures électriques et magnétiques.

Comme les navires militaires et commerciaux sont principalement faits d'acier, ils peuvent être magnétisés et se corroder. De manière générale, les vaisseaux émettent dans leur milieu des signatures magnétiques et électriques grâce auxquelles ils peuvent être détectés, reconnus et ciblés. Le risque perçu et les pertes qu'il pourrait entraîner tant sur le plan économique que sur le plan humain sont à l'origine des travaux de recherche et de développement (R. et D.) qui ont été entrepris en vue de comprendre et de gérer les signatures électromagnétiques (EM) des vaisseaux. Ces études ont porté sur la réduction active et passive des signatures, sur la prévention de la corrosion, sur la détection et la classification, et sur les champs ambiants.

### Résultats

Les champs électriques et magnétiques dans l'environnement marin peuvent être produits par plusieurs sources physiques. En l'absence d'activités humaines, les champs électromagnétiques qui persistent sont produits par d'importantes sources naturelles, telles que le noyau terrestre, le système Terre-ionosphère-haute atmosphère et les courants océaniques cohérents. Ces champs ambiants, également appelés champs naturels, sont perceptibles à l'échelle planétaire et reflètent l'échelle temporelle des sources physiques sous-jacentes.

Le champ géomagnétique terrestre, dont l'intensité ne varie pratiquement pas d'une journée à l'autre, est le principal champ magnétique ambiant. En milieu marin, les

fluctuations du champ magnétique causées par une induction motionnelle entraînent des variations périodiques provoquées par les marées d'origine lunaire et solaire et par la houle. Les périodes occasionnelles d'activité magnétique très intense sont reliées aux éruptions solaires et aux orages électriques qui provoquent des résonances du système Terre-ionosphère. Ces résonances, appelées résonances de Schumann, se propagent dans les océans et sont facilement observées. L'activité sismique et tectonique provoque des variations de très faible fréquence du champ magnétique. Dans les océans, les champs électriques ambiants sont produits par l'induction motionnelle et par l'activité ionosphérique. Lorsqu'elle est causée par une circulation à l'échelle continentale, l'induction motionnelle produit un champ électrique presque constant. Les marées d'origine lunaire, la houle et les courants marins entraînent l'émission de signaux périodiques dans le champ électrique océanique. Toute activité électrique dans l'ionosphère et la haute atmosphère, comme la foudre, produit des variations intermittentes du champ électrique dans les océans.

La fréquence des champs électriques et magnétiques ambiants en milieu marin varie de presque nulle (c.-à-d. champs presque stationnaires) à quelques dizaines de cycles par seconde. L'amplitude des variations est typiquement de  $O(1)$  nT pour les champs magnétiques et de  $O(1)$  uV/m pour les champs électriques.

Les activités humaines menées en milieu marin, telles que les missions en mer, les travaux sur les plates-formes de forage et les activités dans les zones habitées sur la côte, produisent des signatures électromagnétiques localisées. Ces signatures sont localisées, car elles persistent à des niveaux supérieurs ou comparables aux champs ambiants à proximité du vaisseau ou d'une zone habitée sur la côte, mais sont indiscernables du champ naturel à de grandes distances.

Les vaisseaux tels que les frégates et les navires de ligne ont une signature magnétique, car ils sont faits de fer. L'aimantation statique d'un vaisseau de la taille d'une frégate est d'environ 10000 nT mesurée à une profondeur égale à largeur du vaisseau. Les techniques de réduction des signatures, telles que l'immunisation permanente et la démagnétisation, permettent de diminuer cette valeur à environ 1000-2000 nT. Comme la coque et les éléments assurant la propulsion sont faits de métaux différents, ils constituent une pile de corrosion en présence d'eau de mer. Le courant électrique généré par la corrosion produit un champ électrique et magnétique presque statique. Un vaisseau produit des champs électriques alternatifs de même fréquence que la fréquence de rotation de l'arbre de propulsion, ainsi que des harmoniques. Les zones habitées sont des concentrations de sources électromagnétiques. Les champs électriques et magnétiques dont la fréquence prédominante correspond à la fréquence des lignes électriques, soit 50 ou 60Hz, se propagent en mer depuis les zones habitées. Dans le champ proche, le champ électrique produit par la corrosion, par l'arbre de propulsion et par les zones habitées présente une intensité de  $O(1000)$  uV/m et une fréquence se situant dans la plage de 1 - 1000Hz.

Recherche et développement pour la défense Canada (RDDC) a mis en oeuvre un programme de gestion et de détection des signatures électromagnétiques en milieu sous-marin. Ce programme, qui est toujours actif, a permis à RDDC de faire d'importantes contributions dans ces domaines au cours des années. Par exemple, le système actif de mise à la masse de l'arbre de propulsion, qui permet d'éliminer les signatures électriques aux fréquences de rotation de l'arbre de propulsion, a été mis au point à RDDC.

Parmi les compétences que possède aujourd'hui RDDC dans le domaine de l'électromagnétisme, on compte la modélisation computationnelle de vaisseaux, la simulation de rencontres vaisseau-mine, des expériences à l'échelle physique, la détection, la poursuite, la classification, la caractérisation du champ ambiant, la télémétrie magnétique aérienne, l'optimisation de la démagnétisation et des procédures opérationnelles de gestion des signatures.

## **Recherches futures**

La menace que représentent les mines intelligentes à influence multiple continuera de croître au cours des prochaines années, prévoit-on, tout comme la dépendance de ces mines sur diverses signatures électriques et magnétiques. Il faudrait continuer d'affecter des ressources de R. et D. à la résolution de ce grave problème. La réduction des signatures électromagnétiques, la détermination des niveaux tolérables et la définition de tactiques et de procédures opérationnelles constituent toutes d'importantes activités à court terme. L'élaboration de modèles permettant de prévoir la signature en vue de la construction de nouveaux vaisseaux constituera également, estime-t-on, une importante activité à moyen et à long terme. Il y a lieu d'améliorer nos techniques de brouillage des mines en se basant sur la logique qu'elles exploitent.

La mesure des signatures organiques ou embarquées est un autre objectif important des travaux de R. et D. sur l'électromagnétisme effectués par RDDC. La capacité de mesurer ses propres signatures et de déterminer les niveaux de bruit ambiant local dans le théâtre des opérations constitue une capacité habilitante pour un navire militaire. Il serait alors possible de procéder à l'optimisation en temps réel et, ainsi, de s'assurer que la plate-forme se trouve dans un état de risque minimum. Seul un engagement d'envergure et soutenu permettra d'atteindre une telle capacité.

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# List of Abbreviations

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ASG	Active Shaft Grounding
AUV	Autonomous Underwater Vehicle
BEM	Boundary Element Method
CF	Canadian Forces
CFAV	Canadian Forces Auxiliary Vessel
CLDG	Closed Loop Degaussing
CRM	Corrosion Related Magnetic
CPME	Collaborative Planning and Management Environment
DL(P)	Dockyard Laboratory (Pacific)
DMSS	Directorate of Maritime Ship Support
DREA	Defence Research Establishment Atlantic
DREP	Defence Research Establishment Pacific
ELF	Extremely Low Frequency
EM	Electromagnetic
EMAT	Emerging Materials
FMF	Fleet Maintenance Facility
FTE	Full Time Equivalent
ICCP	Impressed Current Cathodic Protection
ISR	Intelligence, Surveillance and Reconnaissance
LRPA	Long Range Patrol Aircraft
MAD	Magnetic Anomaly Detection
MCM	Mine Counter Measures
O&M	Operations and Maintenance
PSG	Passive Shaft Grounding
R&D	Research and Development
S&T	Science and Technology
TIS	Technology Investment Strategy
TMSS	Total Mine Simulation System
UEMS	Underwater Electromagnetic Signatures
UEP	Underwater Electric Potential
WBE	Work Breakdown Elements

# 1 Introduction

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The ancient discovery of lodestone, a naturally occurring magnetic ore which when fashioned into a needle was consistently aligned, led to the invention of the compass circa 4<sup>th</sup> century BC in China [1]. Used then as fortune-telling paraphernalia, the needle evolved into a navigational compass, in about the year 1000. Its use spread from China to Europe to Arabia and was common on ships by 1500. However, it was only in 1600 that the compass' mysteriously consistent directionality was speculated by William Gilbert in London to be caused by the Earth itself being a large magnet [2]. And so began the enduring study of the Earth's magnetic field and its unparalleled role for seafaring vessels.

With the hand-in-hand advances in ship building and navigation, the pursuit for exploration and thence conquest and trade, gave supremacy to oceanic warfare and transport respectively. The world's navies have fulfilled crucial roles in the great wars of the last hundred years [3]. In recent years, primarily naval warfare and large scale naval support was provided in the Falklands [4] war of 1982 and both the Gulf wars. Commercial shipping is a cost effective, relatively safe and environmentally friendly means of transporting goods. In 2003, 41 million metric tonnes of cargo valued at \$7 billion were shipped on the Great Lakes-St. Lawrence seaway alone [5].

Success in naval warfare and oceanic trade is progressively becoming more dependent on scientific support. Quantifying the state of the vessel, the surroundings, detection of possible threats and minimizing the vessel's signatures bear directly on naval strategy during wartime and on standard protocol through peacetimes. Similar though less stringent criteria prevail for commercial ship traffic.

Scientific knowledge to support naval activities has shown remarkable progress over the last 6 decades. The scope of the scientific investigations is broad and covers the spectrum of sea-faring functions. It encompasses vessel design and propulsion, acoustic and infra-red emissions, electric potential and magnetic signatures, surveillance and weapons design, engagement scenarios and military strategy. The wide range of seemingly disconnected requirements spawned similarly disconnected areas of scientific expertise. Consequently, the scientists employed by the research community catering to naval functions have technical expertise in acoustics, electromagnetism, hydrodynamics, structure and sensor design, etc. For historical reasons some of these research areas, e.g. acoustic signatures are mature, while others, e.g. underwater electric potential have received much less attention. However, in recent years this is changing largely driven by a sense of urgency to contain the susceptibility of naval platforms. As a result, the research and development branches of naval defence organizations have made it a priority to minimize all signatures from naval platforms.

In the last 30 – 40 years, there has been a concerted scientific effort employing the full suite of experiments, modeling and simulations, devoted to quantitatively understanding the various signatures of naval platforms. This collective information forms the core of decision-driving knowledge for the operational boundaries of naval vessels and platforms for both wartime and peaceful periods.

Scientific research in maritime electromagnetic signatures begins essentially with Michael Faraday's failed attempt in 1832 to experimentally observe the induction of an electric potential due to fluid motion of the Thames in the Earth's magnetic field [6, 7]. Progress in underwater electromagnetic signatures had been rather sporadic until about 1950 when effort was directed at defusing the lurking threat of residual magnetic mines from World War II. Currently, research in underwater electromagnetic signatures is very much in the mainstream of defence research activities.

In this paper, we present a selective synopsis of maritime electromagnetism. We outline some of the key issues in the subject based solely on the unclassified literature and open science publications. Specific electromagnetic signatures have major defence implications and while they are extensively reported in a large body of classified work, they are not addressed here. Nevertheless, this paper provides a useful overview for those new to the field or for naval staff who need further insight into the physical principles involved with electromagnetic signatures. It is convenient to divide the observed electromagnetic field based on whether the source is a natural physical process and thereby ambient, or a man-made platform and thus localized. For ambient fields we discuss the static geomagnetic field, motionally induced magnetic and electric fields and fields from external sources. For platform signatures we discuss the permanent and induced magnetization and the fields that are caused by corrosion-related electrical currents. We review signature control and corrosion protection measures. We describe the competencies of DRDC in underwater electromagnetism and suggest venues for future studies.

## 2 Ambient maritime electromagnetism

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The Earth's structure, constitution and planetary environment result in a broad spectrum of physical activity ranging from the periodic day and night to the sporadic volcanic eruptions and lightning storms to the near-constant but barely perceptible plate tectonics. These and other natural phenomena give rise to spatiotemporal electromagnetic fields that extend from the Earth's interior, through its continental and oceanic surface to far beyond the upper reaches of its atmosphere.

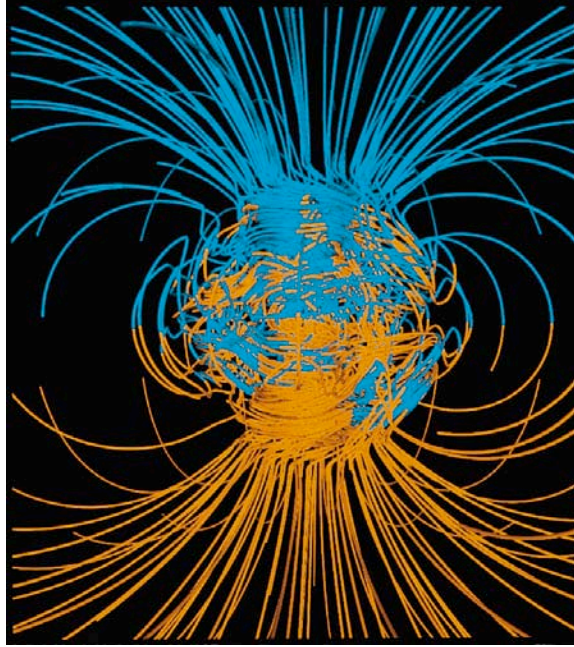
### 2.1 The Earth's geomagnetic field

The largest and primarily quasi-static (on everyday time scales) electromagnetic feature is the Earth's magnetic field or geomagnetic field. It is thought to be generated by the dynamo action resulting from the flow induced in the molten conductive outer core by the Earth's rotational motion. The magnetic field, which encapsulates the planet in a magnetosphere is, at the Earth's surface, well approximated by a quasi-static or DC dipole field. Figure 1 shows the results of a computer simulation of the geomagnetic field of the Earth. The magnetic field in the interior of the Earth is very complex but near the surface it is roughly dipolar. The geomagnetic field has a magnitude of typically 50000 nT at Halifax Harbour and is slowly varying at about  $-100$  nT/year. In fact the Earth's magnetic field has decreased by about 10% over the last 150 years [8]. On longer time scales, it has been inferred that the geomagnetic field has undergone many reversals. However, on everyday time scales, the Earth's magnetic field is largely stationary.

Oceanic water has very nearly unit relative permeability so that the magnetic field at the Earth's surface is practically unperturbed through the air-ocean interface. However, along the sea floor, variations in the bathymetry and geological constitution of the seabed lead to local spatial variations in the magnetic field. These variations arise due to the markedly different permeabilities of the seabed and seawater and due to boundary conditions at a complex interface.

### 2.2 Motional induction: magnetic effects

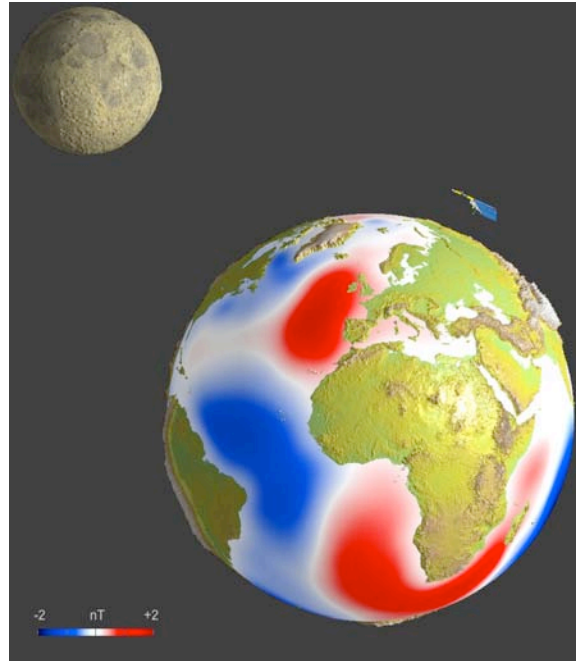
There are several naturally occurring flows in the oceanic system which range from the ocean-scale circulations to the centimeter-scale capillary ripples. When a conducting medium, such as seawater, moves in a magnetic field an electric potential develops. The phenomena, electromagnetic induction, is referred to as motionally-induced induction in the context of maritime electromagnetism. We discuss the basic physics of motional induction in Annex A.2 and describe the physical properties of seawater in Annex B.



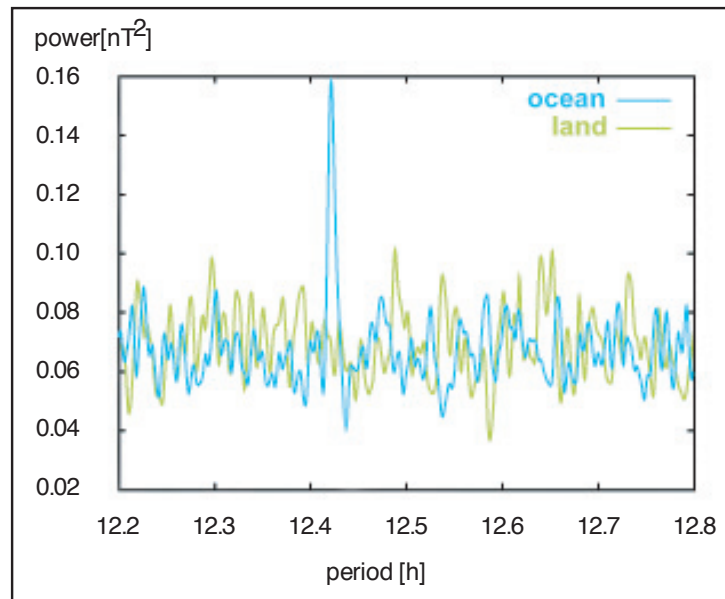
**Figure 1:** Three dimensional computer simulation of the Earth's magnetic field by Glatzmaier et. al. [9]. Inward (outward) directed field lines are in blue (yellow) and extend to about two Earth radii from the core.

The motionally-induced electric field is perpendicular to both the flow velocity and the magnetic field. In turn, the induced electric field drives electrical currents that perturb the magnetic field. Both the induced electric field and the resulting magnetic field have been experimentally measured in marine experiments [7, 10, 11, 12]. Here we first discuss the variations in the magnetic field and then in the induced electric field.

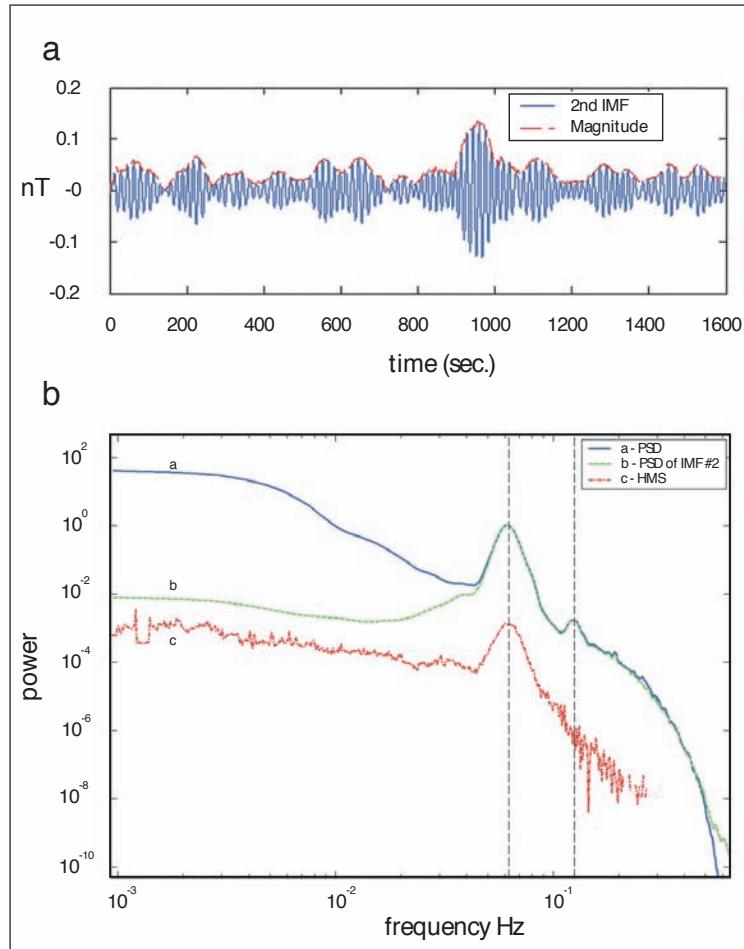
The secondary magnetic field that arises from induced electrical currents has been clearly observed in satellite magnetic data at the lunar semi-diurnal frequency corresponding to the M2 tide [10]. The vertical component of the motion induced magnetic field is of  $O(1)$  nT. While this is significantly smaller than Earth's mean vertical geomagnetic field at mid-latitudes, it is 50% larger than the spectral noise level near the M2 period of 12.42 hours. In Fig. 2 is a rendering of satellite data of the tidal-induced magnetic field over the globe. Two segments of the frequency power spectra of satellite magnetic data are shown in Fig. 3. One trace was taken with the satellite orbiting over land and the other over the ocean. The power spectra of the magnetic field residuals has a significant peak at the M2 period for the over-ocean data which is absent in the over-land data.



**Figure 2:** A rendering of satellite measurements of the tidal induced magnetic field from Ref. [13].



**Figure 3:** Power spectra of satellite measurements of the (induced) magnetic field from Ref. [10]. The peak at the M2 frequency, corresponding to tidal motions, is evident (absent) in the over- ocean (land) data.

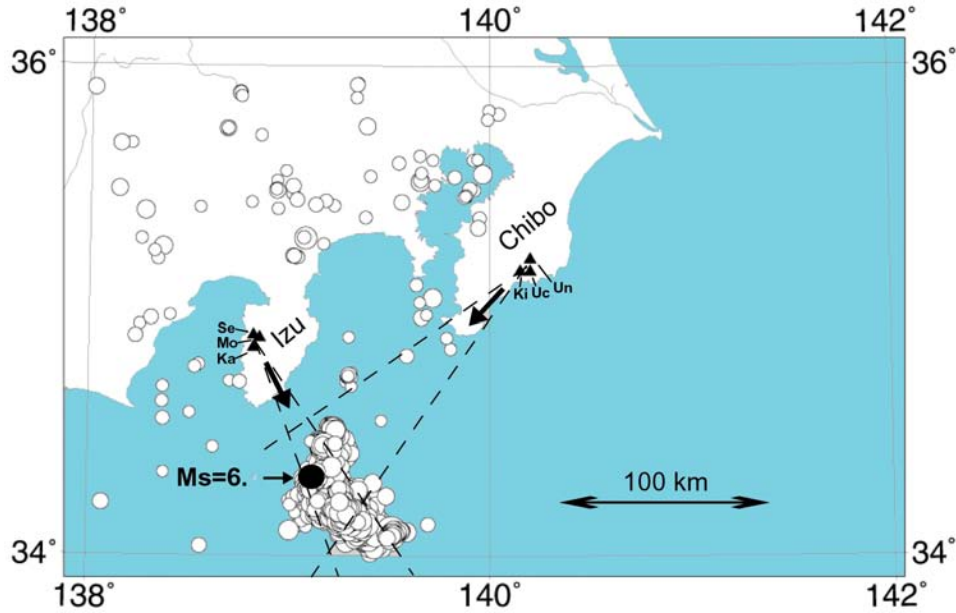


**Figure 4:** A detrended time series of magnetic field data (a). In (b) are shown power spectra of the data in (a). Note the signal at the swell frequency of 62 mHz. Figures from Ref. [14].

At frequencies much greater than the diurnal and semi-diurnal tides, the effects of swells on the magnetic field variation, can also be observed in littoral environments [14]. The length and time scales of characteristic swells in littoral waters are of order 100 m and 50 – 100 mHz. Measurements off the coast of Point Loma (San Diego) show that the magnetic field has fluctuations of the order 0.1 nT at a depth of about 150 m (at the independently-measured swell frequency). See Fig. 4 for representative data. The swell magnitude inferred from the magnetic data were consistent with directly measured swell amplitudes.

Significantly increased seismic activity is sometimes a precursor for an earthquake. When an earthquake is located under the seabed, the preliminary micro-earthquakes and elevated seismic activity result in rarefaction-compression waves in the Earth's





**Figure 5:** Location of seismic activity on July 1, 2000 between 1200 and 0600 hours. Seismic shock epicenters are denoted by the circles. The earthquake epicenter is located with a bullet (●). Magnetic field data are sampled by 6 land-based magnetometers on the Izu and Chibo peninsulas. The magnetometer positions are given by solid triangles (▲). The magnetic gradient and cone are indicated by the arrows and dashed lines respectively. Figure from Ref. [15].

crust. These acoustic waves cause sea floor oscillations that subsequently drive hydro-acoustic waves in the ocean. The resulting flow leads via induction to a magnetic signal that has been repeatedly measured several times in the 1990s [15, 16].

In Japan's Izu and Chibo peninsulas during 2000, three-component gradient magnetometer measurements (land-based) during the period leading up to an earthquake show that the ultra-low frequency magnetic disturbances were measured at typically 0.05 nT for horizontal fields and 0.17 nT for the vertical component at distances of approximately 100 km from the epicenter [15]. The magnetic field gradient magnitude was approximately 1.5 pT/km. The gradient vector pointed towards the source of the seismic activity and tracked the center. Figure 5 shows the direction of the measured magnetic gradients at the Izu and Chibo magnetometer stations.

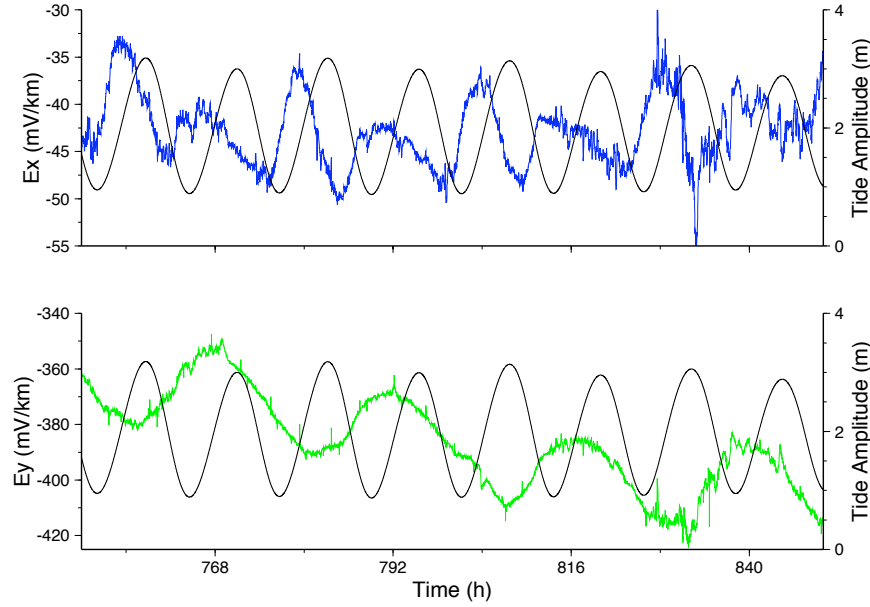
## 2.3 Motional induction: electric effects

The induced electric fields due to the motion of conducting seawater in the geomagnetic field have been theoretically predicted for over 170 years. However, it was not until the 1950s that initial measurements of the effect were made. Theoretical models have since the late 1940s been improved to model more realistically the oceanic environment [7, 17]. The basic physics of motional induction is described in Annex A.2, with the physical properties of seawater collected in Annex B.

Oceanic flows such as the ocean surface currents and the deep water thermohaline circulation which occur due to buoyancy differentials set up by temperature and salinity gradients are coherent large scale flows. The induced electric fields due to these currents is typically measured using submarine and transoceanic telecommunication cables that span from a hundred (across the Florida Gulf Stream  $\sim 125$  km) to a few thousand kilometers (California to Hawaii  $\sim 3900$  km). The large spatial scale and the long receiving line considerably improve the signal to noise characteristics. One typically finds that for average oceanic flow speeds that the induced electric fields are of order  $0.1 \mu\text{V/m}$  except for coastal currents such as the Gulf Stream and the Antarctic Circumpolar Current. Here the signal is a few  $\mu\text{V/m}$  [7].

The deep sea cables essentially sample the induced electric field over the cable length. Variations on shorter scales are averaged out. Since motional magnetic fields are caused by induced electrical currents, measurements of the induced magnetic field can be used to infer the underlying electric potentials. Such transfer techniques are however, strongly model dependent. Nevertheless, the dominant periodic signals that correspond to semi-diurnal and diurnal tidal effects are easily identified.

In confined environments such as shallow channels, electrical signals with various motional origins have been measured [11, 18, 19]. The West Passage at Rhode Island's Narragansett Bay, is a channel with width 2 km and water depth 10 – 15 m. Here a pair of Ag/AgCl electrodes were used to measure the induced electric field over a relatively short separation of 200 m [19]. The time series data show that in addition to the  $\sim 5 \mu\text{V/m}$  M2 tide, higher frequency ( $\sim 60$  mHz) swells induce electric fields that modulate the basic tidal variation. Vertical electric fields  $\sim 10 \mu\text{V/m}$  induced by swell-driven motion have been measured in 50 – 70 m deep water around Point Loma near San Diego [11]. The semi-diurnal and diurnal tidal induced electric fields have also been measured in Barra channel in Portugal's Ria de Aveiro lagoon where like at Narragansett the role of the coast aids in amplifying the signals [18]. In Fig. 6 are shown the variation of the horizontal electric field components with the tides in Barra channel. Similar tide-driven motionally induced electric fields have been measured in the Throat of the White Sea, a strait in Northwestern Russia [20] and in the Strait of Juan de Fuca, a channel shared by the US and Canada on the Washington and British Columbia coast.



**Figure 6:** Two components of the raw electric field measured in Portugal’s Barra channel over a 4 day period. The concurrent, computed tide amplitudes are shown to illustrate the correlation between the two effects. Figure from Ref. [18].

## 2.4 Upper atmospheric electromagnetic couplings

The space bounded between the Earth’s surface and the ionosphere ( $\sim 100$  km above) makes for a resonant cavity for electromagnetic waves. The conducting seawater surface and the weakly conducting ionosphere permit a low-Q resonance of electromagnetic waves. The resonant frequencies, known as Schumann resonances are excited by electrical storms. Since they are the natural modes of the Earth-Ionosphere cavity, the Schumann resonances are selectively propagated from the broad spectrum of electromagnetic frequencies present in lightning. The resonant frequencies vary with the ever-changing properties of the Earth-Ionosphere cavity with on average frequencies of 8, 14, 20, 26, 32, 37 and 43 Hz for the lowest seven modes. In penetrating the oceans, the electromagnetic waves drive currents and are readily detected by Ag/AgCl electrodes [11, 12]. The Schumann resonances are well above the spectral noise floor and, in shallow waters, as many as the first seven modes carry significant electromagnetic energy. The magnitude of these EM waves decay with propagation through the conducting seawater and thus with water depth. The physics of electromagnetic sources in seawater and the attenuation of EM waves as a function of frequency and seawater conductivity is described in Annex A.1. Measurements at about 60 m depth and approximately 1 km from the shore off Point Loma [11] near San Diego have recorded the first five Schumann resonances in both the horizontal electric field components.

**Table 1:** Typical magnitudes and frequencies of various ambient electromagnetic fields measured in and near the ocean.

Magnetic Sources	Magnitude (nT)	Frequency or period
Earth's core	$\sim 32000 - 62000$	$\sim$ DC
M2 lunar tide	$\sim 1$	12.42 hours
Solar ionospheric tide	$\sim 5$	12 hours
Ocean swells	$\sim 0.1$	0.04 – 0.08 Hz
Seismic activity	$\sim 0.02 - 0.2$	0.001 – 0.1 Hz
Schumann resonances	$\sim 0.001$	8, 14, 20, 26, 32, 37, 43 Hz
Electric Sources	Magnitude ( $\mu$ V/m)	Frequency or period
M2 lunar tide	$\sim 5$	12.42 hours
Large scale ocean currents	$\sim 10$	$\sim$ DC
Ocean swells	$\sim 10$	0.04 – 0.08 Hz
Schumann resonances	$\sim 1$	8, 14, 20, 26, 32, 37, 43 Hz
Ionospheric activity	various	0.001 – 5 Hz

The ionosphere is subject to solar tidal forces which drive cyclic motions. Due to conducting constituents in the ionosphere, the tidal motions via induction result in a cyclic variation in the geomagnetic field. This diurnal system is called the geomagnetic Sq (solar quiet) daily variational field. In oceanographic data of the magnetic field there is a strong signal corresponding to the S2 or solar diurnal tide. The signal magnitude is typically 5 nT and is a factor of 5 greater than the M2 magnetic variation [10]. Electric fields in littoral waters and confined geometries (such as Portugal's Barra channel), due to the geomagnetic Sq, are also measured at the S2 period with characteristic magnitudes of 0.5  $\mu$ V/m [18]. Other ionospheric activity that perturb the magnetic field such as geomagnetic storms, continuous and irregular pulsations result in intense but intermittent events in the underwater oceanic electromagnetic fields.

The typical electromagnetic field strengths and frequency for the various ambient fields as measured in and near the ocean are summarized in Table 1.

### 3 Localized maritime electromagnetic signatures

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Electrification and steel fueled the latter half of the Industrial revolution. The last 125 years have seen large growth in dense human settlements. When in coastal locales, the settlements' immense dependence on electricity for industry and day to day usage, creates an electromagnetic "hot spot" near the ocean. The settlements' electromagnetic fields extend out from the coast into the nearby waters [11, 12]. Additionally, the range and incidence of sea-faring activities has increased dramatically (with the greater availability of steel) over the last century. Vessels and oceanic installations such as offshore platforms have not only gotten larger but also multi-functional. The preponderance of steel and the use of onboard electric power in the vessels and platforms renders them as localized hot spots of electromagnetic activity. As with coastal settlements, each sea-faring vessel or offshore platform will propagate electromagnetic fields into the oceanic environment. These spatially local fields will typically dominate over the ambient electromagnetic fields near the vessel or platform. Far from it, the localized perturbations will have decayed sufficiently so that only the background noise persists.

#### 3.1 Permanent and induced magnetization

The structural elements in large oceanic vessels and platforms contain a significant fraction of steel. Since iron is ferromagnetic, the vessel exhibits a permanent magnetization. Additionally, the Earth's geomagnetic field induces a magnetization in the steel. Consequently, a large primarily steel vessel will have a nearly constant permanent magnetization and an induced magnetization that depends on its geographical location. The magnitude and direction of permanent magnetization depend on the size of the vessel and the crystalline alignment in the iron. On the other hand, the induced magnetization is dependent on the vessel's geometry, its content of ferromagnetic metals particularly iron, and on the ship's location (latitude, longitude) and heading. It is difficult to determine *a priori* the induced magnetization theoretically and in practice one assumes that it is proportional to the vessel's mass and to the Earth's magnetic field. The constant of proportionality can be deduced for simple shapes and symmetrical volumes or can be measured.

It is well known that even oceanic vessels of modest displacements have sufficiently large magnetizations to significantly perturb the local geomagnetic field [21]. These perturbations or anomalies are rather easily measured by seafloor magnetometers in littorals and by airborne magnetometers at distances in excess of 100 m. This magnetic signature has crucial implications for naval defence. A class of torpedoes and mines are triggered by the local magnetic field of a vessel [22]. Introduced by

Germany during World War II, the use of the magnetic mine proliferated to such an extent that sophisticated mine sweeping measures have had to be developed. With the advent of low power digital electronics and logic, magnetic mines have gotten “smarter” and consequently the minimization of a naval defence vessel’s magnetic signature is more important than ever.

### **3.1.1 Measurements and models**

The magnetic signature of a vessel can be measured at a distance by sweeping flights of airborne magnetometers over a vessel. This type of measurement has been dubbed MAD (Magnetic Anomaly Detection). More refined signature measurements are typically obtained by sailing the vessel over a range outfitted with underwater magnetometers.

Magnetometer design and development has been an important part of naval defence research. There are, broadly speaking, two categories of magnetic field sensors, the total field magnetometer and the vector magnetometer [21, 23]. The total field magnetometers measure only the magnitude of the magnetic field and so are insensitive to sensor rotations. As a result they are often used in airborne trials where the towed sensor is free to rotate. The vector magnetometers measure the component of the magnetic field aligned with the sensing element. In this case the magnetometer measurements are corrupted by rotations of the sensor. Often, a pair of sensors on a baseline are used to measure the gradients of the total or vector components of the magnetic field.

There are many types of magnetometers such as the Zeeman optical magnetometer (to measure intense solar fields) and induction loop magnetometer (to measure the rate of change of the magnetic field). There is much on-going research in improving magnetometer performance. Recent work in magnetometer design and development has focused on laser based systems, on SQUIDs (Superconducting Quantum Interference Device) and on fluxgates with the goal of obtaining a resolution of 1 pT at 0.1 Hz [21, 24, 25, 26].

The MAD signal of a typical naval defence vessel can be detected at distances of a few hundred meters by mobile magnetometers. However, the data is rather primitive in that the vessel is represented as a point dipole furnishing only the strength and direction of the dipole as parameters. Given that most measurements are likely to be made at distances comparable to the vessel length, the dipole approximation is probably valid [27]. Other data variables that are needed are the vessel-to-sensor distances for total field measurements and the sensor velocity for gradient measurements. The magnetic anomaly can be determined from the data by dereferencing the Earth’s geomagnetic field. Data inversion and optimization algorithms are then

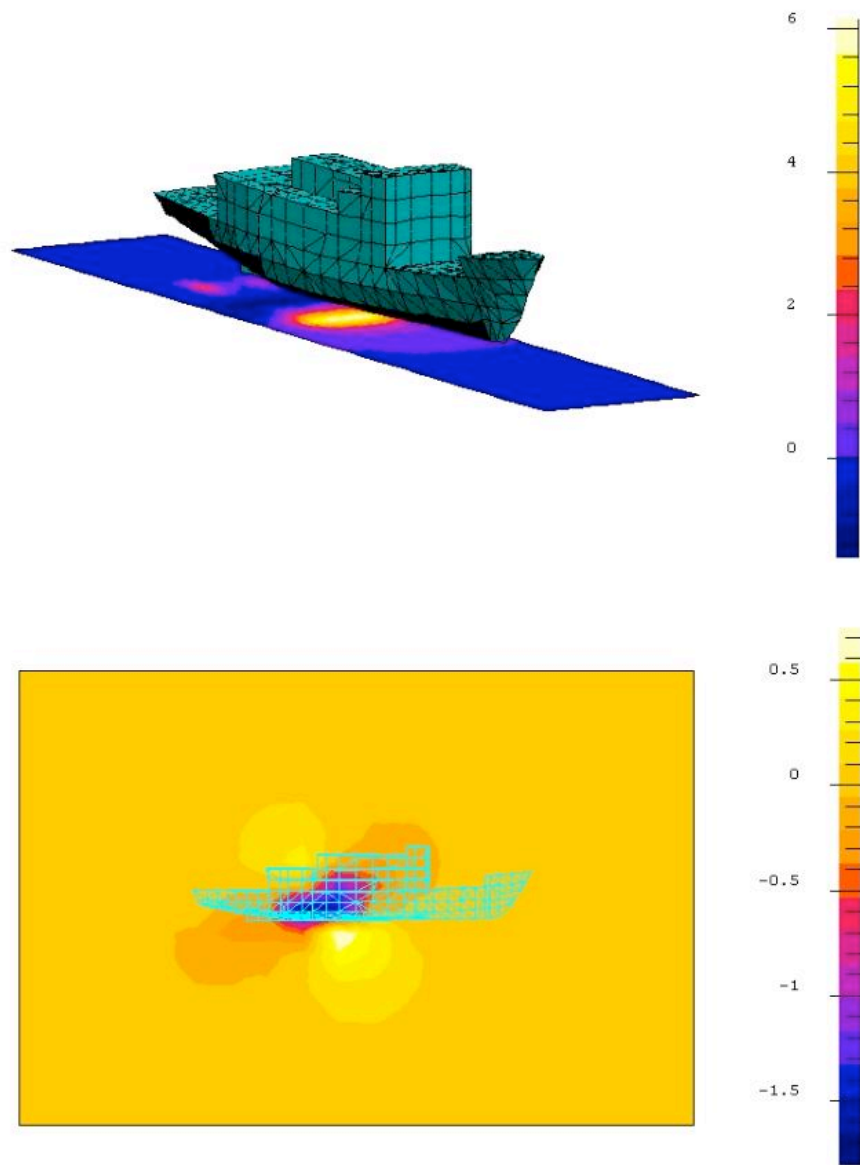
used to deduce from the residual data the set of probable permanent and induced magnetization parameters for a point dipole embedded in the vessel.

Since the MAD algorithms require the approximate separation between the vessel and the sensor it is suited to ranging cooperative vessels. Non-cooperative vessels can be detected using MAD, however, there is greater variability in the dipole parameter estimates. Canadian Forces Auxiliary Vessel (CFAV) *Quest* has been a cooperative target in three MAD trials [28]. Without any magnetic silencing measures, CFAV *Quest* caused a magnetic anomaly of about 100 nT at a distance of about 80 m near Halifax Harbour. From this data it was determined that CFAV *Quest* has a magnetization equivalent to a dipole with magnetic moment of about  $7 \times 10^7$  nTm<sup>3</sup> [27]. Compared to typical naval defence frigates, the CFAV *Quest* is roughly half as long and has 40% of the total displacement. Therefore, without signature reduction systems, frigates and other large naval vessels will have significantly larger magnetic source parameters and anomalies. At distances of about 1 km, the field would drop to the 1 pT range with spatial gradients on the order of 1 fT/m [21]. Dipole fields are discussed in Annex A.1.

Near-field magnetic signature profiles of vessels are richer data than the MAD source parameters. Here, the magnetic field data is measured along, across and away from the vessel with distances of closest approach several times shorter than with MAD. The spatial trends, which provide information on the vessel size and aspect ratio, help distinguish between classes of vessels. However, meaningful profiles can only be obtained at near distances and so cooperative vessels have to visit ranging facilities. Given the military-strategic value of the magnetic signature profiles, data from ranging naval defence vessels are classified. Recent measurements on a German frigate show that the shapes of the induced magnetic profiles are not too different from those obtained by modeling the vessel as a hollow ellipsoid and even closer to those computed by finite element methods [29]. The profile of the longitudinal field has gross features that identify the bow-to-stern direction, while the other profiles aid in determining the vessel's beam and its distance from the sensors. Peak magnetic fields at range depths are 10000 – 15000 nT for typical frigates and 20000 – 30000 nT for in-service tankers.

Magnetic models of oceanic vessels span from simple theoretical constructs to detailed computational frameworks. Theoretically, a vessel can be represented as a collection of elementary dipoles, spheroids or ellipsoids. The resulting magnetic field can then be calculated. A general description of electromagnetic sources is given in Annex A.1. Often these models can be too simple to be fair representations of the vessels, especially in the near field. Numerical schemes to compute the magnetic field of a vessel use finite element techniques. In these schemes the vessel's geometry is accurately represented and physically relevant boundary conditions are imposed. The differential or integral equations are then solved to determine the magnetic field. In





**Figure 7:** A finite element model of CFAV Quest with magnetic field predictions on a plane below and to the side of the vessel.



Fig. 7 is a finite element model of CFAV *Quest* with magnetic field predictions below and to the side of the vessel.

### 3.1.2 Deperming methods and Degaussing systems

The magnetic signatures expose all ferromagnetic vessels to risk from mines. Given the risk to seamen, the military handicap borne when a defence vessel is hit, and the economical costs, magnetic signature reduction for warships is essential. Research in magnetic silencing is directed towards designing magnetically quiet vessels and on reducing the magnetic signatures of currently operational vessels. In view of the service lifetime of vessels, the latter aspect has perhaps received more attention.

The current protocol for reducing the vessel's prevailing magnetic signature is two-fold. First the vessel is depermed *i.e.* it is treated so as to temporarily eliminate the magnetization. Second, the induced magnetization is countered by passing electrical currents through strategically placed on-board coils so as to set up an opposing field and thus null out the net field. This procedure is referred to as degaussing.

Steel-hulled vessels have permanent magnetizations that reflect their magnetic history. The permanent magnetization is dependent on the local crystalline orientation of the iron, on the magnitude and direction of the mechanical stresses that were endured during construction and residually present, and on the ambient magnetic field during the construction of the vessel. Deperming seeks to erase this magnetic history. The conventional deperming procedure is called Flash-D [30]. The concept is to demagnetize the vessel's longitudinal magnetization, and to bias the permanent vertical magnetization so as to almost exactly cancel the locally induced vertical component.

Flash-D is implemented by subjecting the vessel to a sequence of "shots" of an external magnetic field. Each shot consists of a stepwise incremental ramping of the externally applied magnetic field components to a predetermined maximum amplitude and then a stepwise decremental ramping to zero. With each subsequent shot, the polarity of the applied magnetic field is reversed and the amplitude reduced linearly. The maximum amplitude is chosen to be large enough so that all magnetic domains are aligned. In this way the magnetic history is erased. However, for the larger, highly-permed vessels facilities are not in place to deliver the required external fields.

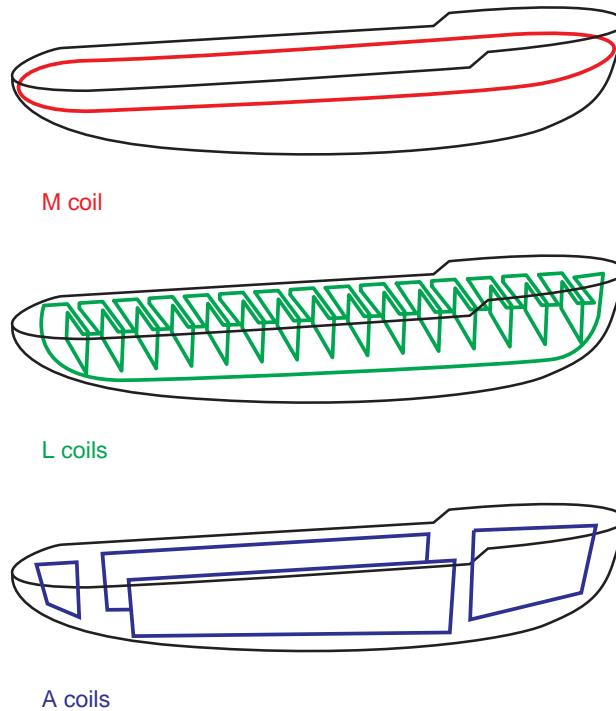
After the deperming treatment, ideally the vessel is nearly demagnetized. In reality it actually has a vertical permanent magnetization that is counter to the assumed induced vertical component so that the total magnetization vanishes to within a few percent. This situation does not persist for long since the vessel is constantly subjected to the Earth's geomagnetic field and to mechanical stresses. Thus a recently depermed vessel relaxes to a state in which the locally induced magnetization is the dominant magnetic signature. On a longer time scale of months, components of the

permanent magnetization recover to values comparable to those before the deperming treatment. Therefore, it is necessary to range the magnetic signature of in service vessels regularly to determine when deperming is necessary. It is unfortunate that temporal changes in the permanent magnetization after deperming have not been adequately monitored. Consequently, technical knowledge of the utility of a deperm and the needed treatment frequency are unavailable.

There has been recent research dedicated to improving the predictability of the deperming procedures. The Flash-D method has been virtually unaltered in several decades and there is now some indication that alternative demagnetization procedures may be more efficient [30]. Based on the Preisach model for magnetic hysteresis, an alternative deperming method called “Anhysteretic Deperm” has been tested on laboratory scale. The results show lesser variability in the vertical magnetization than the traditional Flash-D process.

Recent trials have indicated that the permanent magnetization changes significantly with vessel deployment. From two very similar MAD measurements on CFAV *Quest*, it was concluded that the permanent longitudinal dipole moment had decreased by approximately 10% between October 2002 and March 2004 [27]. Significant variation of the permanent magnetizations of a US surface naval defence vessel have also been observed. Magnetic rangings at deployments in San Diego (September 2000), in Sydney (December 2000) and on return to San Diego (April 2001) [31] showed large changes in the permanent magnetization of the ship. The mechanisms responsible for the variability in the permanent magnetization have yet to be elucidated. One suggestion is that the magnetization responds to stresses encountered by the vessels during deployment. The effects of stress on ferromagnetic materials is an important research venue that has led to an understanding of how the magnetic signatures of submarines vary with the dive profiles. Here the stress due to the water head at the dive depth leads to changes in the magnetization and hence in the signatures by the reversible magnetostrictive and the irreversible magnetomechanical effects [32]. The signatures change by over a factor of two during typical dives. Whereas, stress related changes in the magnetization and signature are expected for submarines, there is little direct evidence to suggest that surface vessels are subjected to similar levels of stress and hence to irreversible permanent magnetization changes.

In spite of regular deperm treatments, the induced magnetic field of modest oceanic vessels is easily measurable and therefore poses a risk. A suitable solution is to counter the signature *in situ* by setting up a magnetic field of equal magnitude and opposite sign to the induced field. This is accomplished by driving currents through various on-board coils. The process is called degaussing. Depending on the level of magnetic silencing required, a vessel will have one or several coils that work to counter the different components of the induced field. The basic coil is the M or main coil which counters the vertical component, with other coils strategically located to counter

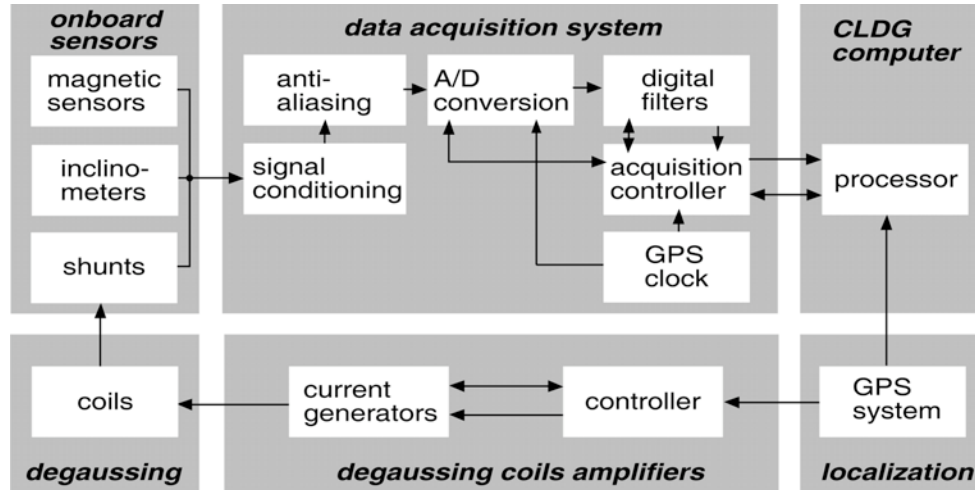


**Figure 8:** A schematic of the basic ship board degaussing coils.

longitudinal (L coils) and athwart (A coils) components. See Fig. 8 for a schematic. Supplementary coils targeting subtler effects are often used. Presently, there are two on board installations in use: the open and closed loop degaussing systems.

In the open loop system, predetermined DC currents are passed through the coils to render the vessel magnetically quiet. However, from time to time, the appropriate currents have to be recalculated to account for drifts in the permanent magnetization. This means that the vessel has to be regularly ranged for the open loop degaussing to be effective. Scientific research is invaluable at the design stage of the degaussing coil assembly. Computational modeling to optimize the parameters for the degaussing system such as the number, placement and electrical current in the coils is vital for effective magnetic silencing.

On vessels with an existing degaussing system, the free parameters are the DC current settings for the coils while respecting the overall power utilization. The optimal setting is the one that minimizes the magnetic signature. A typical warship, such as the Canadian Patrol Frigate, with as many as 23 coils poses a daunting optimization task. By suitably breaking up the problem into induced and permanent magnetizations, and into the vector components, finite element modeling can then be applied to the 5 M, 14 L and 4 A coils to seek the optimal parameters for the DC current [33].

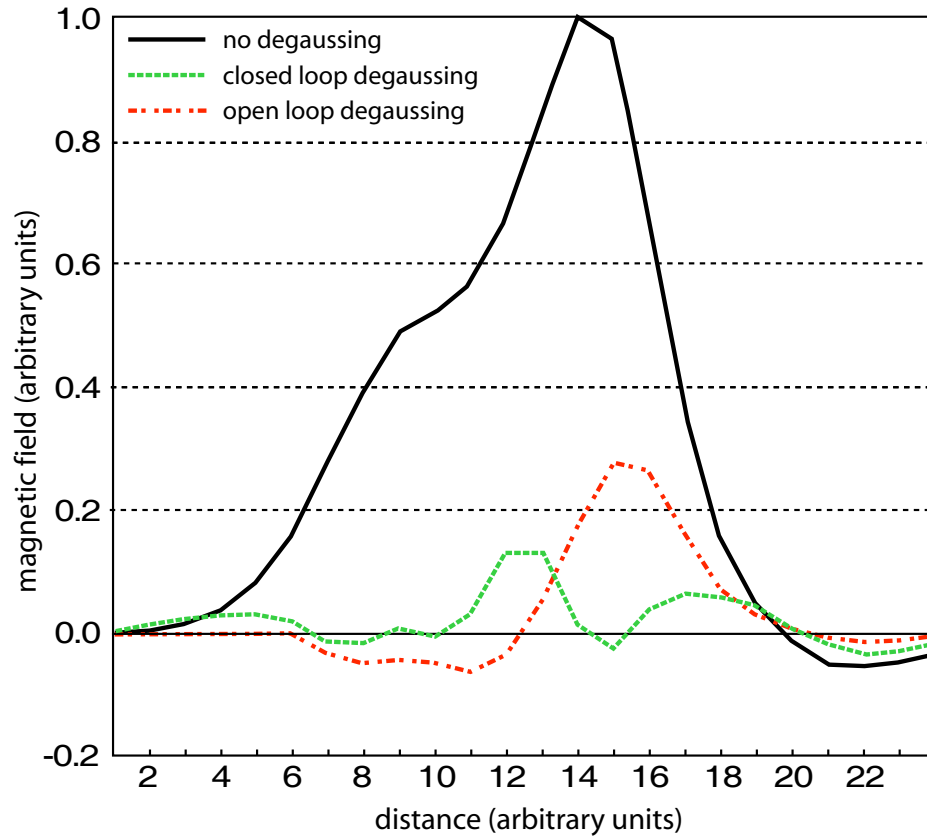


**Figure 9:** A schematic showing the operational aspects of a CLDG system.

Whereas this optimization procedure has been computationally demonstrated it is not common in practice. At ranges, the currents in the various degaussing coils are determined experimentally through an iterative procedure consisting of several measurements along various headings.

The stringent functional requirements of degaussing systems has spawned an effort to study and experimentally demonstrate new techniques on smaller scale-models of naval vessels especially warships. A French team has designed and constructed a Physical Scale Model (PSM), complete with degaussing coils and magnetic flux sensors, to verify their computational modelling [34]. They have matched the experimental and computational geometries to within 1%. Magnetic field measurements from their PSM are accurately represented by the computations suggesting that the numerical methods could be extrapolated to actual vessels.

In the last 10 – 15 years, closed loop degaussing (CLDG) has emerged as a promising solution for magnetic signature management. While robust, the open loop system does not have the capability of adapting for unpredictable magnetic signature changes from permanent magnetization drifts, from repositioning of cargo and from external sources in the local environment. Addressing this issue, the stand alone CLDG system has been designed to dynamically sense changes in the local magnetic field environment and in response to implement real time compensatory measures [35]. The installation consists of a collection of sensors and data acquisition control with real time analysis coupled by a sophisticated electronic feed back logic to optimize the coil currents. When operating effectively, the CLDG system renders the vessel magnetically silent at all times and in most environments. A schematic of the operation of a CLDG system is shown in Fig. 9.



**Figure 10:** Magnetic field measurements on a non-magnetic hull MCM with open and closed loop degaussing. Figure from Ref. [35]. The black (red) [green] curves show the vertical magnetic field without (with open loop) [with closed loop] degaussing.

Recently, the US, French and Italian navies have each installed and evaluated CLDG systems on mine countermeasures (MCM) ships. The US Avenger MCM, the French Circe MCM and the Italian Gaeta MCM, have hulls constructed from composites of non-magnetic materials. The US and French CLDG systems have demonstrated an 80% compensation for magnetic anomalies which is a considerable reduction in signature when compared to the open loop process [35, 36]. See Fig. 10. Similar results were obtained by the Italian group. CLDG systems on vessels with metallic hulls are not common but are being developed. At present, physical scale models and computational tools have been used to study the CLDG of vessels with magnetic hulls [35]. Preliminary results show that the laboratory scale experiments and the numerical predictions are in reasonable agreement.

Notwithstanding the advances made in the scientific and technical aspects of degaussing, there are yet deficiencies that need to be addressed especially as the vision of

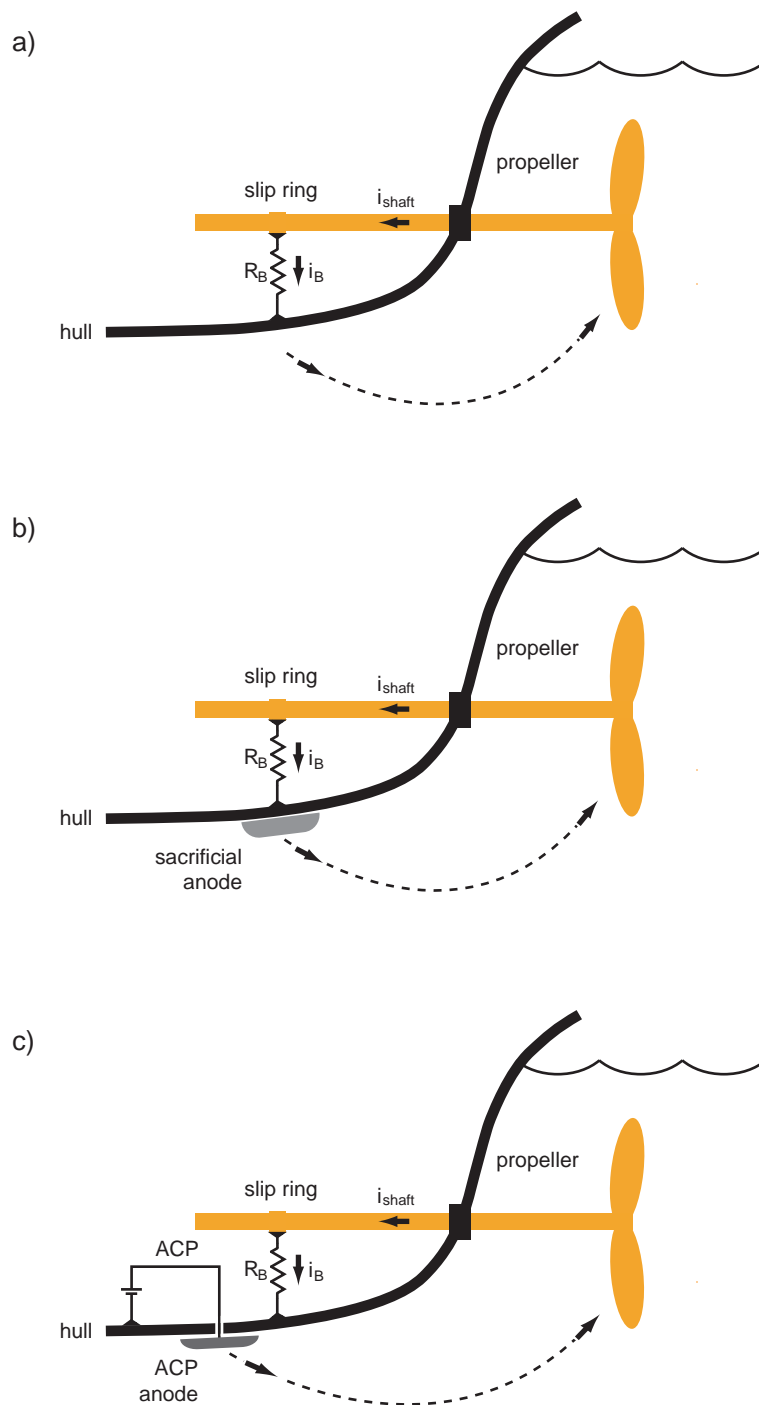
the “All Electric Ship” gains momentum [37]. Theoretical models and their computational implementations are becoming increasingly complex as they aim to realistically model the degaussing scenario. One aspect that has commanded much recent attention is the shielding characteristics of a vessel’s steel [38, 39]. Degaussing coils and other electrical current carrying equipment generate electromagnetic fields that propagate into the underwater environment. To the extent that they do so, they pose a signature threat. Therefore understanding the underwater penetration of static and alternating electromagnetic fields generated inside a metallic vessel is an important problem. Aside from the geometry, the problem involves three material media with steel, a ferromagnet, and so with a variable permeability. Scientists in the Netherlands and France are actively tackling this problem with both theoretical and experimental methods [38, 39].

### **3.2 Corrosion related electromagnetism**

Most oceanic vessels have a hull of steel construction and a nickel-aluminum-bronze (NAB) propeller system. When these dissimilar metals are submerged in seawater they form an electrochemical cell [40]. Seawater consists of hydrated ions which react with the ship’s metals. At the propeller the reaction is simply electrical involving only the transfer of electrons from the metal to the seawater. This is the cathodic reaction and since the metal does not participate it remains intact. On the steel hull, however, the anodic reaction involves the oxidation of the iron. There are three typical oxidation mechanisms by which the steel is corroded. The mechanisms result in the steel’s iron dissolving into the seawater, being converted to an oxide or a hydroxide. In all cases, the steel hull degrades due to corrosion.

The anodic and cathodic reaction processes occur in a well defined electrochemical cell with seawater as the electrolyte. Electrical currents must flow in the circuit defined by the anode, electrolyte and cathode. Since the geometry is complicated and the hull’s metallic characteristics are non-homogeneous, the current paths are difficult to discern. However, an electrical current must flow in the ship and be completed by a path through the seawater as shown schematically in Fig. 11a. From these currents arise the corrosion related electric and magnetic signatures of the vessel.

The operational lifetime of a sea-faring vessel can be drastically reduced by corrosion and its susceptibility to mechanical failure is greatly increased. Spectacular accidents, attributed to corrosion-related failure litter the naval archives. Some of these have claimed the lives of numerous seamen, others have culminated in extensive environmental damage and all have been economically costly. Including replacement costs, maintenance and downtime, the total annual cost to the US shipping industry due to corrosion is approximately \$2.7 billion [41]. The incidence and cumulative impact of corrosion-related problems has spawned a science-based industry dedicated to mini-



**Figure 11:** The panels (a), (b) and (c) are schematics of the effective electrolytic cell for a typical vessel without, with passive and with active cathodic protection measures, respectively.

mizing corrosion on sea-faring vessels and offshore platforms. Corrosion prevention research has yielded anti-corrosion paints, as well as passive and active corrosion protection systems.

Research in corrosion protection of vessels is an important and valued scientific pursuit in both the ship commercial and defence sectors. The primary protection mechanism is the application of an insulating paint, where possible, to all the submersible parts of the vessel. As long as the paint coating remains intact, corrosion is almost entirely halted. With time, the paint coating deteriorates and corrosion ensues. As a result secondary protection mechanisms are necessary to facilitate vessel operation for long durations. There are two secondary protection systems in current use: the passive (sacrificial anode) and active (impressed current) protection systems. Both operate by forcing the steel to be cathodic so that it will not corrode.

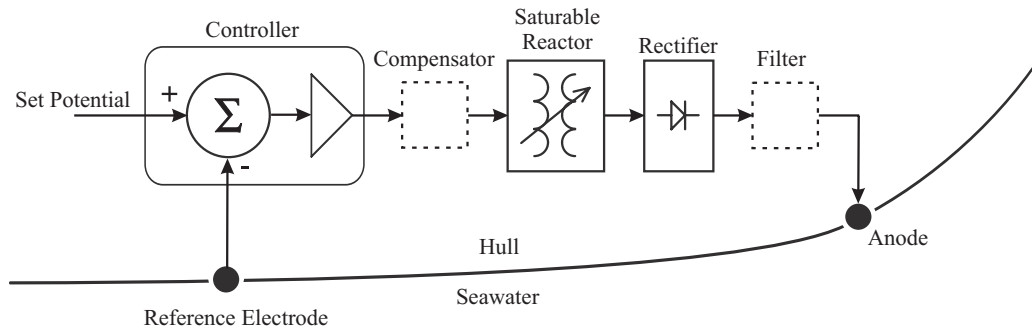
In the passive galvanic system the steel hull is forced to be cathodic by distributing metals such as Zinc, Magnesium or Aluminum over the hull [40]. Since these metals have more negative half-cell potentials with seawater than steel, they become anodic and corrode in place of the vessel's iron. A schematic is shown in Fig. 11b. It is for this reason that the method is referred to as the sacrificial anode cathodic protection system.

Active cathodic protection is implemented with the Impressed Current Cathodic Protection (ICCP) system [40]. In the ICCP system, anodes located on the hull are used to drive an electrical current to the rest of the steel hull as illustrated in Fig. 11c. The impressed currents render the entire hull to be cathodic and so free from corrosion. The anodes are composed of a variety of materials such as graphite, high-silicon alloys or platinized metals.

The ICCP systems used by the Canadian Navy are based on the feedback design shown in Fig. 12. The units have been developed to be electrically durable by using a saturable reactor and a simple rectifier circuit. They typically last for the life of the ship. To protect the hull from corrosion the rectifier output provides a current that maintains the reference electrode at a value of  $\sim -850$  mV, significantly more negative than the  $\sim -650$  mV half-cell potential of steel.

Whereas, secondary corrosion protection systems alleviate the oxidation of the steel hull, they more often than not, aggravate the electromagnetic signature at long ranges [42]. Nevertheless, due to economic and safety considerations, the use of corrosion protection systems is essential. Today, their use is widespread. Almost all recently built commercial and defence vessels are outfitted with ICCP systems and many smaller vessels such as fishing boats and yachts are equipped with "mini-ICCP" modules.





**Figure 12:** Schematic of ICCP control system: DRDC improvements, shown in dashed boxes, include a high current filter to remove power frequency emissions and a phase compensator to improve stability.

### 3.2.1 Static and Extremely Low Frequency (ELF) electric field signatures

The electromagnetic fields or signatures that are driven by the corrosion depends on both the distribution and magnitude of the electrical current. Whereas the electric potential that drives the corrosion is solely determined by the difference between the metal-seawater electrochemical potentials, the rate of corrosion however, is set by the electric current that flows through the cell [40]. The corrosion current is thus determined by the effective circuit resistance. Unfortunately, the resistance is a complicated and obscure function of numerous parameters, a partial list of them being the integrity and porosity of the paint coating, and the oxygenation and rate of flow of the seawater. In fact, in laboratory experiments the measured current density varies by over a factor of 2 with oxygen concentration, by over a factor of 4 with temperature of the seawater and by an astounding two orders of magnitude with electrolyte flow rate [40]. Consequently, the *a priori* determination of the electromagnetic signatures due to corrosion is an imposing task.

Electrostatic potential differences that persist on various parts of the ship's surface set up the DC electric field. The gradient of these potential differences propagate through the ocean and can be measured offboard the vessel using electric field sensors. An example of an electric field signature sometimes referred to as the Underwater Electric Potential (UEP) signature is shown in Fig. 13. This signature data of the NURC (NATO Undersea Research Center) research vessel Alliance was recorded at the Bedford Basin Degaussing Range on July 23, 2001 using electric field sensors mounted on the seafloor in a water depth of 17 m. The raw electric field data shown are filtered to separate the static component of the signature from the higher frequency components. The static part corresponds to an average over the electric potential difference while the higher frequency components are due to periodic modulation of the resistive path

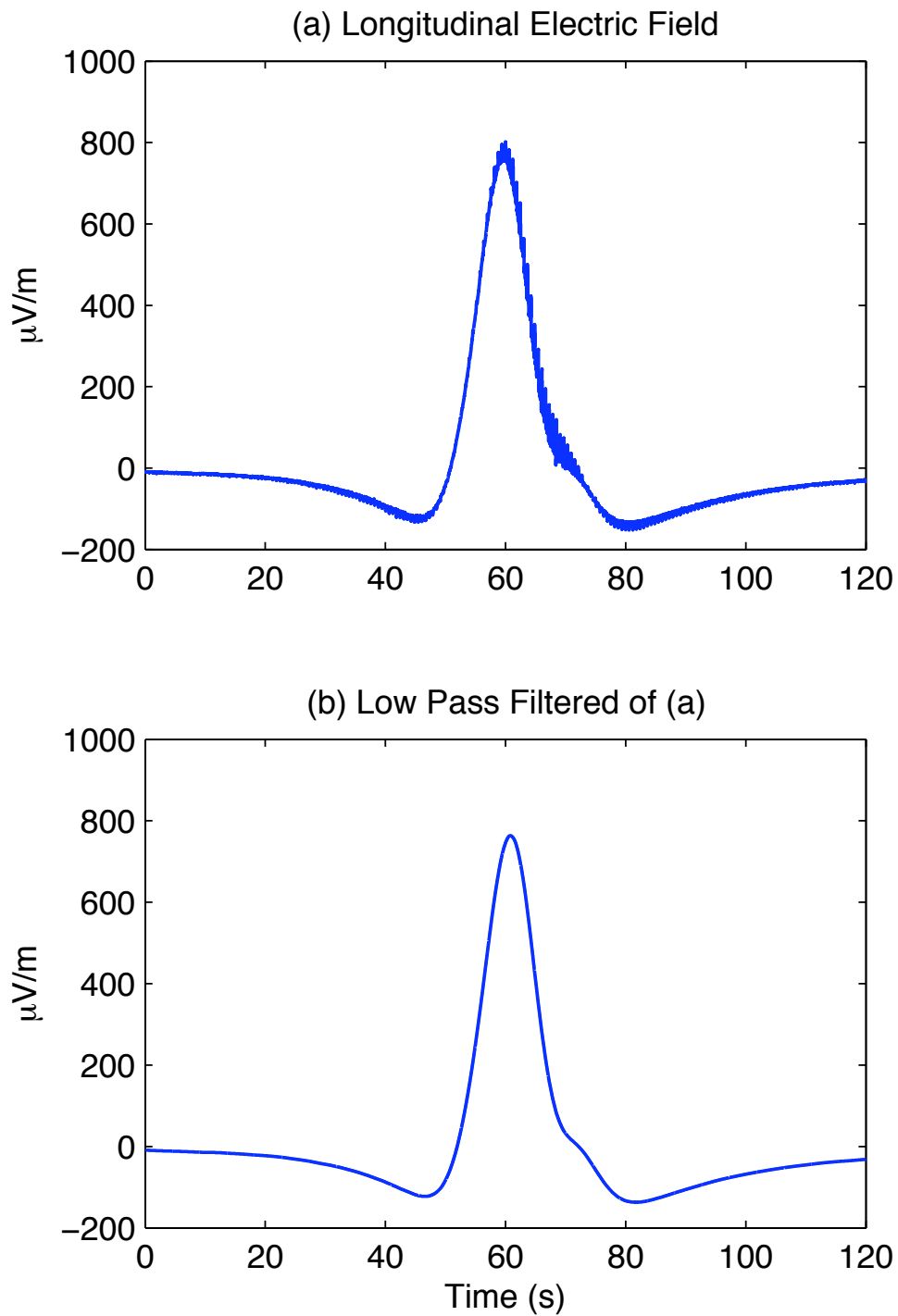
by the vessel's propulsion system [22, 43, 44]. These fields are collectively called ELF fields and typically are between 1 – 1000 Hz. They are countered by active signature management techniques discussed in Section 3.2.3.

Rarely can a vessel's underwater electric field signature be measured in a variety of operational conditions. One is always limited by the location of sensors which are generally in shallow water where a naval vessel is severely limited operationally. An attractive and reliable alternative is to perform measurements on a laboratory-scale vessel which is referred to as Physical Scale Modeling (PSM). A vessel of interest, say a warship, is accurately reproduced but on a length scale that is about a hundred times smaller. In Fig. 14 is a picture of a physical scale model of a Canadian Patrol Frigate. The model warship is to be directly related to the actual vessel and so care must be taken in ensuring that the materials, structures, anti-corrosion systems and electrolyte are correctly scaled. The vessel speed can be mimicked by the flow rate of the electrolyte and several physical parameters such as water temperature, oxygenation and depth can be conveniently varied. The laboratory-scale experiment can then be adequately instrumented to furnish data on underwater electric potentials measured at the model's surface and elsewhere. The results can be directly compared to those obtained from numerical models and then extrapolated to the scale of an actual vessel. Preliminary work on PSM and measurements of the static electric field have been promising and have validated numerical codes [45].

### **3.2.2 Static and Extremely Low Frequency (ELF) magnetic field signatures**

The electric current due to difference in electric potential on various parts of the vessel generate a magnetic field. This magnetic field is termed the corrosion related magnetic (CRM) signature since it is a result of electrical currents from corrosion or corrosion prevention devices. Since the current is modulated due to periodic variations in the resistive path between the propeller and the hull, the slowly oscillating current gives rise to a static and an ELF magnetic field. Direct measurements of CRM signatures have seldom been reported. Instead, sophisticated models to accurately compute the corrosion related magnetic field with various combinations of sacrificial anodes and ICCP currents have been developed.

The numerical scheme that is particularly well-suited to the problem is the Boundary Element Method (BEM) [46]. In this scheme, the surfaces are discretized and assigned the appropriate boundary conditions. The discretized difference equations are then iteratively solved. Several codes have been developed internationally and are used to design optimal cathodic protection systems. Depending on the sophistication of the chosen code, the model accounts for the shape of the vessel below the waterline, the number and locations of sacrificial and ICCP anodes, the integrity of



**Figure 13:** Longitudinal electric field of the NURC research vessel *Alliance* recorded at the Bedford Basin Degaussing Range on July 23, 2001 in 17 m of water. The data is filtered to separate the static signature from the higher frequency components.



**Figure 14:** A picture of a physical scale model of the Canadian Patrol Frigate developed at DRDC Atlantic to study the underwater electric field signature.

the anti-corrosion paint layer and the various polarization curves. Electrochemical potentials are assigned to the boundary elements on the vessel's surface and from these a surface current density is calculated using polarization data. The electric potentials and normal derivatives are then computed by successive over-relaxation. From the converged values at the discretized boundary, the static magnetic field is computed.

The computations show that the magnetic field is very small with a maximum near the propeller. Severe paint damage can increase the signature several hundredfold and reduce variation along the vessel's length. The degree of protection conferred by the ICCP system varies with the magnitude of the impressed current [46].

### **3.2.3 Impressed Current Cathodic Protection (ICCP) and Active Shaft Grounding (ASG) systems**

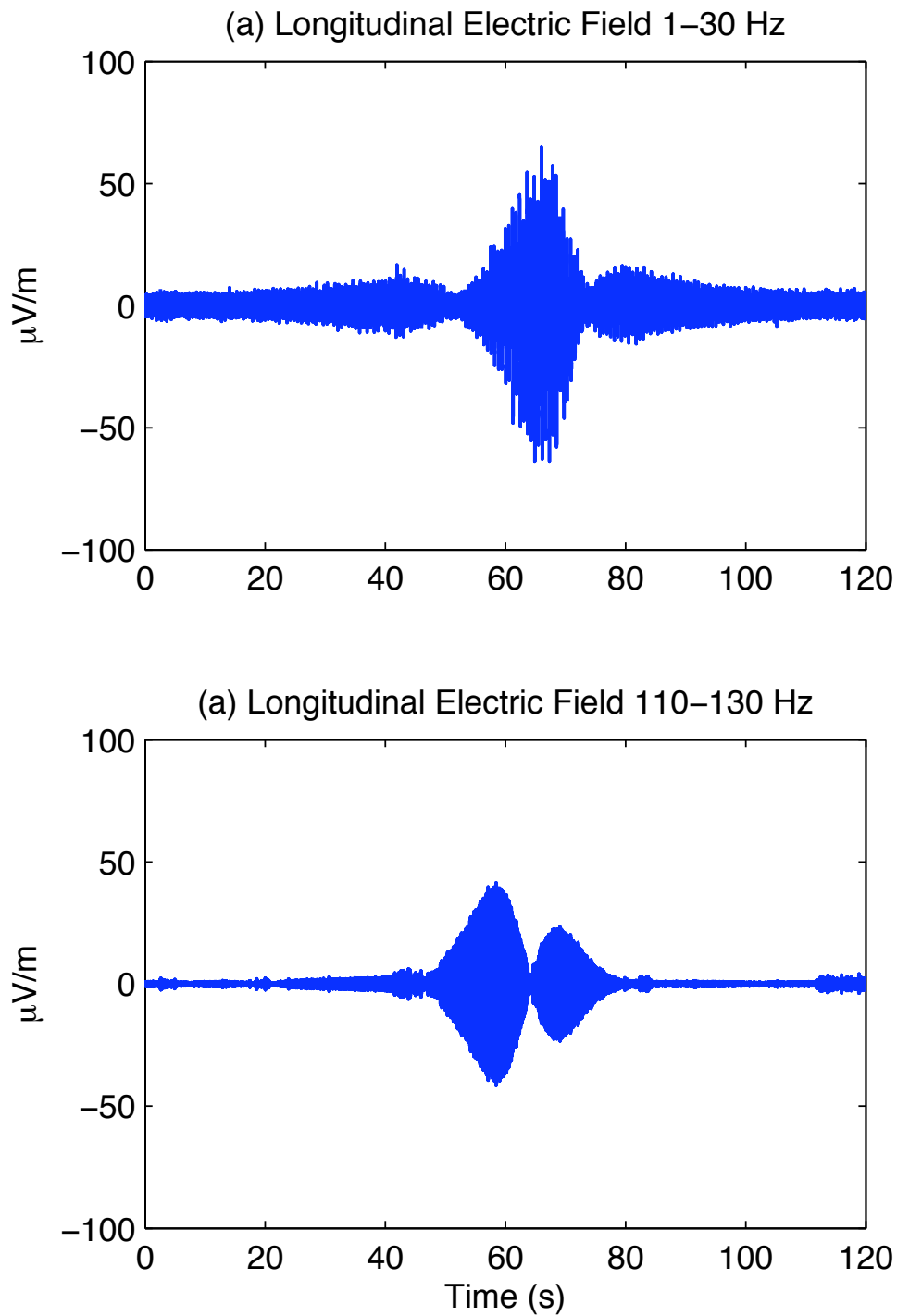
Protecting a vessel against corrosion led to the development of the ICCP and ASG systems. Both, are nowadays, common equipment on steel hulled vessels. Not only are they important for their corrosion prevention aspect but also from the perspective of underwater electromagnetic signatures.

The goal of the ICCP system is to prevent corrosion of the steel hull. This is accomplished by impressing an electrical current from the ICCP anodes to the steel hull in effect forcing the hull to be cathodic at a well defined DC voltage. In the ICCP system of Fig. 12 this DC voltage is obtained by rectifying the 60 Hz power provided from the ship's generator. The presence of power frequency signals in the electrical current at the rectifier output is widely considered to have no significant effect on the degree of corrosion protection. From a signature perspective, if left unfiltered, an easily detected ELF signal at the ship's power frequency is pumped directly into the ocean. Such signals are best detected using electric field sensors but are also detectable using magnetic field sensors. To remove the power frequency component of the rectifier output DRDC designed the ICCP filter [47, 48]. The ICCP units on the CPF have also been observed to break into oscillation. DRDC corrected the problem by designing a phase compensator circuit to improve the system's stability. A complete review of DRDC improvements to the ICCP system is available in [49].

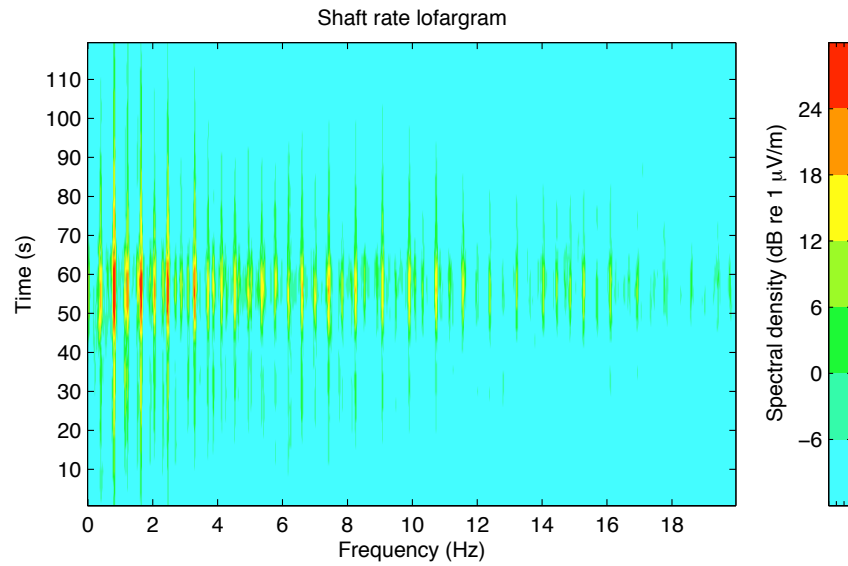
The ELF band roughly covers the frequency spectrum from 1 – 1000 Hz. Since seawater is electrically conducting, the ELF EM fields rapidly decay with increasing frequency (see Annex A.1) thus only low frequency fields are effectively propagated. There are two primary mechanisms which produce ELF signatures as a result of the direct coupling of electrical currents into the seawater: the propeller shaft modulation and the vessel's electrical power generation. In Fig. 15 the electric field signature data of the NURC vessel Alliance is filtered to isolate the shaft rate (1 – 30 Hz) and power frequency signatures (110 – 130 Hz). On Canadian Naval vessels DRDC has provided countermeasures to correct for both of these mechanisms.

The shaft rate ELF fields originate from periodic modulation of the resistance due to rotary couplings between the shaft and vessel body. The corrosion currents which flow around the hull will find a return path through the bearings which support the shaft. The resistive path of this current will vary as the shaft rotates causing a modulation of the corrosion current at the shaft rate and its harmonics. Fig. 16 shows the frequency content of the trace plotted in Fig. 15a, the shaft rate harmonics are clearly visible. In principle, the ELF shaft rate signature can be eliminated by grounding the shaft to the hull.

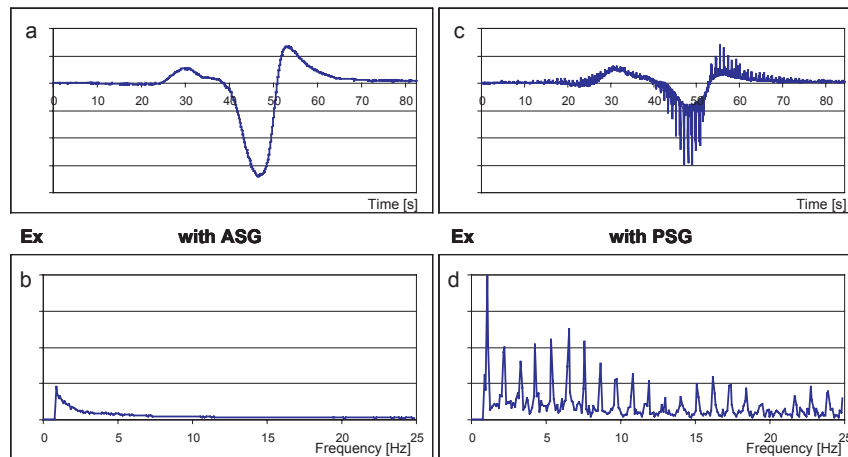
Early work in this area was pursued to provide corrosion protection to the vessel and made use of a simple grounding strap between the hull and the shaft. This method, when used for ELF signature management, is referred to as Passive Shaft Grounding (PSG). In Figs. 17c and d are shown underwater electric field signature measurements on a frigate with PSG at the Aschau range in Germany. Note that superposed on the DC longitudinal electric field profile are large spikes corresponding to the ELF alternating fields with abundant signal energy in the 1 – 25 Hz shaft rotation range.



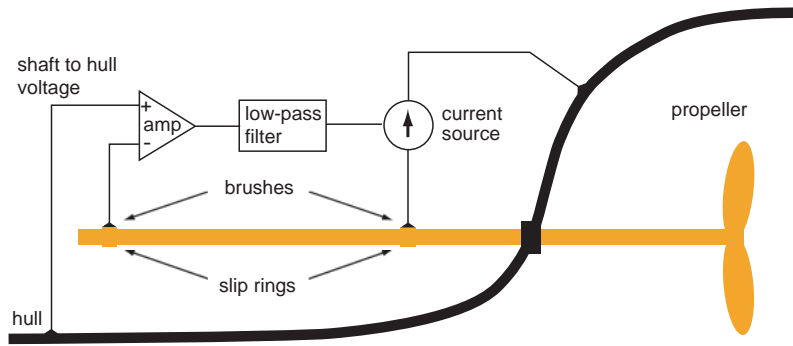
**Figure 15:** Longitudinal electric field of the NURC research vessel *Alliance* recorded at the Bedford Basin Degaussing Range on July 23, 2001 in 17 m of water. Data has been filtered to isolate the shaft rate signature and the power frequency component of the ICCP system.



**Figure 16:** Lofargram of the shaft rate signature of the electric field signal shown in Fig. 15a



**Figure 17:** In (a) and (c) are raw underwater electric field signatures with active and passive shaft grounding respectively. In (b) and (d) are the corresponding frequency power spectra. Note the almost complete suppression of the alternating electric field with active shaft grounding. Figure from Ref. [50].



**Figure 18:** Schematic of the ASG system.

Addressing the shaft ELF signature in PSG vessels, R. Buckett and D. J. Evans [51] designed the first active system which used a feedback network to sense the shaft to hull voltage and drive a current to bring the shaft to the same potential as the hull as shown in Fig. 18. This remedy is known as Active Shaft Grounding (ASG). The team at Aschau have demonstrated that the ASG almost entirely suppresses the alternating electric field signature as shown in Figs. 17a and b. Whereas initially designed for corrosion protection, the signature control aspects and benefits have now been realized [52]. Today the units are marketed for their signature control and corrosion protection aspects.

### 3.3 Miscellany of other electromagnetic effects

In measurements of the underwater electric field near coastal settlements there is always a strong signal at the 60 Hz (or 50 Hz) power line frequency with somewhat weaker harmonics at 120 and 180 Hz (or 100 and 150 Hz). Off Point Loma near San Diego, recent trials have been conducted to study the distance from shore and the depth dependence of the underwater electric field using anchored platforms and variable buoyancy floats respectively [11, 12]. Data from these independent trials reveal that the signal at 60 Hz varies consistently with the notion that it originates at the shore and propagates down from the ocean surface. Propagation of electromagnetic fields is discussed briefly in Annex A.1. In particular, the signal decays with distance from the shore and is attenuated by the seawater conductivity in the same way as a plane electromagnetic wave incident on the ocean surface. The power line signal presumably varies with the intensity of electromagnetic activity at the shore and so the source strength depends on the size and industrial nature of the coastal settlement and on the time of day. At distances of about 10 km from the shore and 50 m below the ocean surface, the underwater electric field signals at 60 Hz are strong, typically 40 dB above the ambient noise level [11, 12].



**Table 2:** *Typical magnitudes and frequencies of various localized electromagnetic signatures measured in the ocean.*

Magnetic sources	Magnitude (nT)	Frequency (Hz)
Static magnetization	10000	< 1
Static magnetization (after deperm)	8000	< 1
Static magnetization (with degaussing)	< 2000	< 1
Corrosion related magnetic field	< 1000	< 1
Electric sources	Magnitude ( $\mu\text{V}/\text{m}$ )	Frequency (Hz)
Static electric field	1000	< 1
Alternating electric field	< 1000	1 to < 1000
Alternating electric field (with ASG)	< 1	1 to < 1000
Human settlement related fields	< 100	60, 120, 180
Sea floor exploration related fields	various	1 to < 1000

Sea floor exploration aimed at discovering the composition of the Earth is a localized activity that uses electromagnetic sources and receivers. These studies constrain the models constructed by geophysicists and oceanographers about the formation and evolution of the Earth's structure [26, 53]. This exploration is also aimed at locating reserves of minerals and energy resources. Electromagnetic sub-sea floor exploration is often carried out by towing arrays of dipole sources and receivers. Sometimes a combination of stationary and towed instruments are used. The exploration process is termed a sounding and consists of generating electromagnetic signals from dipole sources and measuring the transmitted fields. The signals are of low frequency and are often coded pulses. There are several likely paths between the sources and receivers with varying impedances. Some paths are almost exclusively through the sea floor while others may involve a reflection at the air-water interface. The collected data are then analyzed with a sub-sea floor layer model, and based on internal self-consistency, layer conductivities, porosities and interface depths are deduced. Typical conductivities are 3.5 S/m for seawater, 0.3 S/m for sedimentary rock and 0.001 S/m for bedrock. Models of physical properties of seawater are presented in Annex B. Certain anomalies in the conductivity and porosity can indicate the possible presence of hydrocarbon fuels and gas hydrates.

The typical electromagnetic field strengths and frequency for the various localized electromagnetic signatures measured in the ocean are summarized in Table 2. The magnitudes for fields emanating from a typical frigate are quoted at standard ranging distances.

## 4 DRDC's competencies in maritime electromagnetism

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DRDC has a long history of R&D activity in underwater electromagnetism. The earliest defence research work in Canada was to develop a method to degauss ships during World War II. The work was carried out at the Degaussing Experimental Office at the Halifax Dockyard in 1940 and within a year became the Naval Research Establishment - the beginning of DRDC [54]. Shortly thereafter, research began in the use of coils of wire placed across the mouth of Halifax Harbour to detect the intrusion of German submarines by magnetic induction. By the end of the war, operational systems had been developed which included elaborate DC amplification and dynamic compensation for the effects of geomagnetic fluctuations [54]. Research was also carried out on the detection of submarines using electrodes to sense their underwater electric potential (UEP). Again, an operational system was deployed in Halifax Harbour and it was used to gather DC electric signature data on Allied ships steaming in and out of the harbour. The knowledge gained about UEP later contributed to the development of Cathodic Protection, one of Canada's greatest defence research achievements. It can be argued that underwater EM signature research is the most enduring theme in Canadian defence research.

Canada was one of the first countries to adopt ASG for its naval ships and today Ottawa-based W. R. Davis Engineering Ltd. is one of the leading manufacturers of ASG systems. The Davis ASG systems are modelled on a design developed at Defence Research Establishment Pacific (DREP) [55]. Impressed Current Cathodic Protection (ICCP) was developed at Defence Research Establishment Atlantic in the 1950s and 1960s to control corrosion of ship hulls. In the 1980s the ELF EM signature caused by the ICCP was essentially eliminated by adding passive filters to remove noise in the impressed current.

More recently, DRDC Atlantic provided mine vulnerability assessment during Operations Friction and Apollo and assisted the Fleet Maintenance Facility (FMF) with the development of a forward EM ranging capability. DRDC Atlantic has also made significant contributions to the Canadian Forces (CF) EM ranging facilities on both the East and West coasts. State of the art electric and magnetic sensors, data acquisition systems and operational procedures have been developed and implemented at the CF EM ranges.

## 4.1 Organization of DRDC maritime EM signature research

The present DRDC research program is governed by the Technology Investment Strategy (TIS) [56] which partitions research into 22 different activities. EM signature research falls under the Signature Management activity of the TIS. Within this activity, EM signature R&D contributes to the Underwater Signature Management Strategic Objective which has the following goal:

“Investigate maritime platform acoustic, electromagnetic and wake characteristics to assess potential solutions to current and future signature problems. The program will develop analysis, modelling and counter-measure capabilities, perform full-scale measurements, provide independent technical advice to DND, preserve the knowledge base required for major acquisitions and solve in-service problems.”

EM signature-related research is carried out entirely at DRDC Atlantic with activities at Dockyard Laboratory (Pacific) (DL(P)), Emerging Materials (EMAT) and the Underwater Electromagnetic Signatures (UEMS) group. In response to the TIS which was published in 2002, a new group was formed at DRDC Atlantic called Integrated Signature Management (ISM). ISM has the mandate to exploit the signature management products developed throughout DRDC and demonstrate “integrated” signature management concepts to minimize over-all platform susceptibility.

While the TIS provides the direction and structure for DRDC research, the work is carried out within the framework of the R&D Thrusts. EM signature research is done for the Maritime client group in Thrust 1C, Maritime Underwater Warfare and Thrust 1G, Naval Platform Technology. Each thrust is subdivided into Projects which are further subdivided into Work Breakdown Elements (WBE).

Following is a summary of DRDC’s current EM-related research program structure and resources. The information is derived from the DRDC business management system CPME (Collaborative Planning and Management Environment). Figures are for human resources, expressed as Full Time Equivalents (FTE), and research contract funds. The reported FTEs are approximate as some individual science workers contribute to areas other than EM research. Financial resources are also approximate as they do not reflect capital and operations and maintenance (O&M) allocations. Financial contributions from external partners are included in the financial resource figures, but are estimated based on available information.

Presently there are approximately 10 science FTEs dedicated to EM-related research in DRDC. Approximately \$600k of research contract funds are allocated each year to this field. In-kind contributions from US and UK partners for DRDC’s MAD program

are equivalent to \$100k and direct DRDC support for the National Research Council (NRC) Convair research aircraft for the MAD program is \$125k per year. Table 3 provides a snapshot of activities and resources at the time of writing.

## 4.2 Current DRDC competencies

DRDC's current EM competencies include computational and numerical modelling, physical scale experimentation, full scale measurements and ranging, detection and tracking, signature optimization and active shaft grounding refinement.

Computational models have been developed for the UEP and magnetic field of a Canadian Patrol Frigate (CPF) [57, 58] and CFAV *Quest* [59]. The UEP is modelled using the boundary element method while the magnetic model is based on a finite element code. Other modelling activities include development of oblate and prolate spheroidal representations for magnetization [60, 61] of naval vessels and underwater construction [62, 63, 64]. Simulations, in particular the Total Mine Simulation System (TMSS), has been used extensively at DRDC Atlantic to obtain safe-zone projections for naval vessels in mined waters.

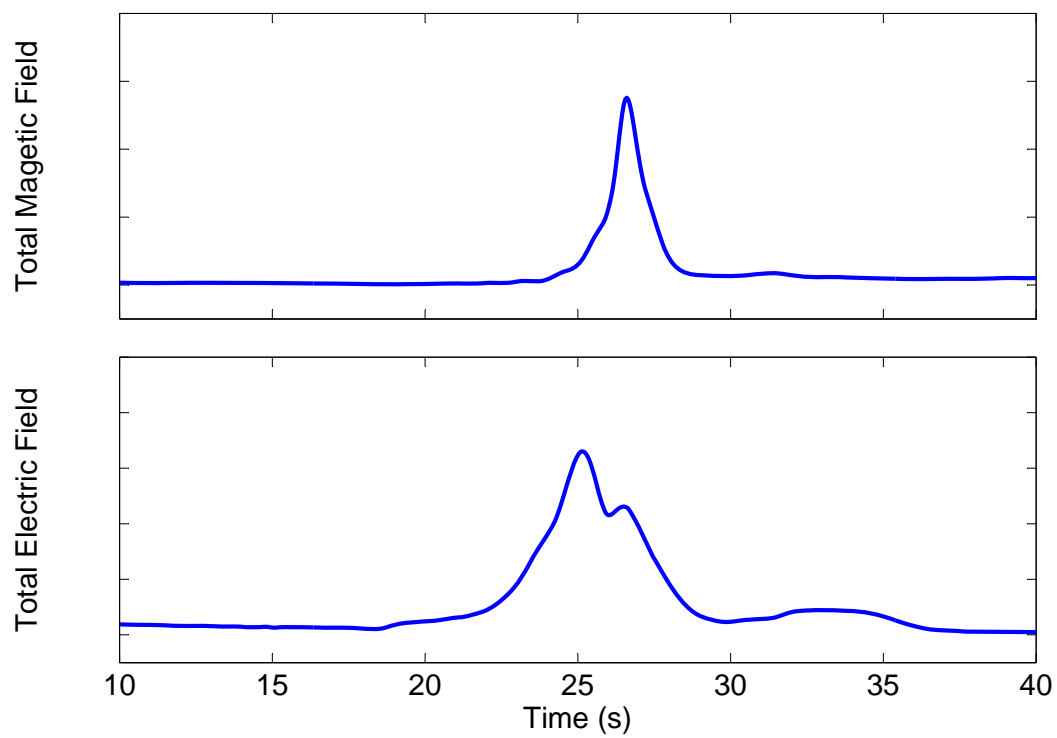
An accurate physical scale model for the CPF has been designed, constructed and used to measure the UEP in a controlled laboratory environment [65]. UEP measurements of cooperative targets are undertaken when possible. These include measurements at the hull surface and at range depths. Electric and magnetic measurements of mine clearance divers are a recent activity [66]. In Fig. 19 are shown a diver approach to a sensor package representing a mine and the corresponding magnetic signature.

The UEMS group at DRDC Atlantic collaborates regularly with international partners in joint naval exercises. These trials typically involve one or more cooperative naval vessels, and an array of electric and magnetic sensors. The data is analyzed for detection and classification [67], tracking [68], and background characterization [69]. UEMS is also active in airborne-magnetic detection by MAD. The research vessel *Quest* has been a cooperative target in three recent MAD trials [28]. DRDC Atlantic has assisted in developing the operation procedures that are practiced at the East and West coast ranging facilities. Ranging data on CF naval vessels is regularly studied by DRDC Atlantic. A recently developed capability is forward EM ranging in operational theaters. This capability requires DRDC Atlantic involvement in theater and was successfully demonstrated with Canadian vessels in the Persian Gulf.

Other R&D activity in underwater electromagnetism involves degaussing optimization [33], electromagnetic wave propagation and scattering [70].

**Table 3:** DRDC EM research activities and resources

<b>Project 11cn</b>	<b>Underwater Data Networks and Sensors for Autonomous ISR Systems</b>
WBE 11cn02	<i>Electromagnetic NetALS Communications: \$130k/year</i> This work is a joint activity with the US and Norway that is mostly related to underwater EM detection and communication.
<b>Project 11cj</b>	<b>Naval Platform Target Strength Prediction, Measurement and Modification</b>
WBE 11cj18	<i>Passive Signature Models: \$130k/year</i> The goal is to quantify benefit of advanced degaussing for CPF and MCDV platforms.
WBE 11cj19	<i>Active Target Strength and Jamming: \$100k/year</i> To demonstrate shipboard signature modification for mine jamming.
WBE 11cj20	<i>Organic and Fixed Ranges: \$60k/year</i> To support CF EM ranging requirements through improved integrated ranges and to definition requirements for forward ranging capability.
<b>Project 11cy</b>	<b>UWW Miscellaneous Activities</b>
WBE 11cy02	<i>Improved MAD Systems: \$125k/year</i> To develop and implement advanced MAD systems and to investigate geomagnetic coherence and the effects of ocean dynamics on MAD. DRDC support to the Convair for MAD is approximately \$125k and there are in-kind and cash contributions fro international partners of approximately \$100k.
<b>Project 11go</b>	<b>Integrated Ship Signature Management Testbed</b>
11go03	<i>Underwater Signature Integration: \$40k/year</i> Deployable, integrated signature measurement system for divers, autonomous underwater vehicles (AUV) and signatures research.
11go04	<i>UEP signature modelling: \$30k/year</i> To develop tools for evaluating existing and future ICCP systems and associated UEP signature.



**Figure 19:** A mine clearance diver approach to a sensor package and the corresponding electric and magnetic signature.

## 5 Future directions

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Future directions for the near term are dictated by the Thrust Advisory process that takes into account naval requirements on a time frame of several years. While the TIS provides a measure of longer term vision, it has been difficult to interpret for the purpose of allocating resources. Presently a new strategic vision for DRDC and the Department of National Defence is being developed. Known as the Science and Technology Strategic Plan, it will attempt to better align DRDC capabilities with CF requirements for both immediate and 10 – 15 year time frames.

The draft version of the S&T Strategic Plan available at the time of writing [71], indicates that effort will be structured along 11 different S&T areas which are further subdivided into approximately 50 S&T Challenges. These challenges represent the most important technical obstacles that must be overcome in order to deliver capabilities to the CF. Most EM research described in this paper will be carried out in the “Protection:Physical” S&T area under the challenge known as “Reduced observability through active and passive signature management”. While the names and details of the descriptions may change before the S&T Strategic Plan is released, it is clear that all signature management activities will be grouped together under a single S&T Challenge. Some EM research related to sensing or communication will fall under the “Intelligence, Surveillance and Reconnaissance” S&T area.

There are two principal forces that steer the allocation of R&D resources in EM signature research. The first is risk mitigation. To lose a naval vessel and any of its complement in a conflict is a tremendous blow to navy capability. The second force is economic. Naval vessels are prohibitively expensive and so their structural integrity for safe use over a lengthy tenure is a guiding principle. Risk mitigation favors exploitation of the best available EM signature management technology to reduce the signatures to the greatest extent possible. This goes beyond use of signature management equipment such as ASG and degaussing systems, but includes use of non-magnetic materials and careful design of the platform. The cost of naval vessels favors an emphasis on designing and building economical ships with smaller crews.

Underwater EM signatures expose naval vessels to mine threats. These autonomous explosive devices are triggered by a sensing logic. Modern mines use multiple sensors and sophisticated detection and triggering algorithms. It is widely believed that the threat from these “smart” mines is steadily increasing and is likely to be the most significant threat to naval operations in the near term. This is particularly true in light of recent Canadian defence policy that promotes operations in the littoral zone and the concept of naval support for forces ashore [72]. Therefore, future R&D efforts will be aligned to counter the risk posed by mines. Needless to say, this can only be achieved if one understands how mines work. The rudimentary elements are: sensors and a logic. The sensors measure physical fields such as acoustic, electric, magnetic,

pressure and seismic. The logic determines whether the sensors have measured a vessel signature of interest and executes a firing decision. Therefore progress is required in understanding the operation of existing and future mines in order to optimally allocate resources for EM signature management research.

The signatures exploited by modern mines include DC magnetic, acoustic, pressure and seismic. In the future DC electric, and ELF magnetic and electric fields are expected to be exploited as well. The most dangerous mines respond to two or more influences, the most common combinations being; acoustic/magnetic, magnetic/pressure and acoustic/magnetic/pressure. The details of signature detection and firing logics are highly classified. However, in generic terms, the logics often consist of threshold-triggered wake-up, a duration of signature monitoring (such as signature rate-of-change or look-backs), and a firing decision tree. Accordingly, there are two ways to mitigate the mine threat: to be invisible to the mine sensors or to “fool” the mine logic. The former is achieved by reducing the signature levels or signature management and the latter by propagating signals on which a mine does not fire, which is called mine-jamming.

Signature reduction calls for a continuation in the current DRDC program for EM signature management. Since mines are multi-influence, an integrated approach to underwater signatures to reduce the susceptibility of naval platforms is required. Static and ELF electric and magnetic signature management methods should be improved and operational guidelines created for use by the CF. Magnetic deperming of the Victoria class submarines can only be done in the US or UK at the present time and the cost is prohibitively high. DRDC should work with the CF and DMSS to plan a Canadian deperming facility on the East coast. Active degaussing optimization schemes and more economical solutions for active shaft grounding need to be developed. Predictive signature models must guide future construction of vessels. And since smaller vessels generally have smaller signatures, the future will likely include special-function lighter craft. The acceptable or tolerable signature magnitude will be determined by studying the level of ambient EM noise in various operational theaters. Thus, there is a demand to collect electric and magnetic field data of the oceanic background.

Jamming protocols have to be developed for naval missions in potentially mined waters. Intelligence units would be relied upon to provide a suite of mine logics. Given the set of logics, a jamming sweep can be developed. In the absence of intelligence on the mine logic, probably the safest jamming protocol would be to disguise the vessel signature as ambient noise. Scientists would have to be creative in this aspect.

The key to successful signature management is signature self-awareness. In the future, it would be beneficial to have platform-based self-awareness capabilities. Systems must be developed to measure EM signatures, of vessels and of the local environ-



ment, in the operational theater. This could include forward ranging systems such as those already developed or appropriate sensors on the platform itself. The latter is more desirable as continuous monitoring of the signature from onboard the platform would allow for real time signature awareness and dynamic signature management responses. One example is a closed-loop degaussing system. However, substantial physical and engineering barriers must be overcome in order to demonstrate successful organic monitoring of many EM signature types. Magnetic anomaly detection has traditionally been used for detection of submarines. However, modern, ultra-sensitive magnetometers may be exploited to perform rapid magnetic forward ranging of CF assets. CF long range patrol aircraft (LRPA) will soon be equipped with state of the art magnetometers. Since these aircraft are typically deployed with CF ships, exploiting the LRPA as a MAD ranging platform could be very effective operationally.

## 6 Conclusion

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Magnetism has played an important role in sea-faring activities for over a thousand years, electric phenomena for over a hundred years. Today, the field of oceanic underwater electromagnetism remains rich in areas that merit scientific investigation. Advances in EM sensing technology have increased the threat from underwater mines, a trend that is expected to continue. The threat must be countered through continued research in the nature of the ambient EM environment, EM signature management and EM countermeasures.

In this report, we have presented an unclassified review of electromagnetic phenomena in the maritime environment with the purpose of providing guidance for future DRDC investment in EM research. The ultimate goal of DRDC EM research is to minimize the susceptibility of CF assets to EM threats. We have thus focused on compiling an overview description of the various electromagnetic signatures, our ability to model them and how they compare to the magnitude and variations in ambient electromagnetic fields. Generally, near-field EM signatures of naval platforms greatly exceed ambient levels, hence the susceptibility to detection. Furthermore, the time scales of ambient field variations and those of vessel signatures are quite distinct. As a result, at the current time, naval vessels can be rather easily distinguished from background electromagnetic fluctuations in the near field. In mined waters, a vessels' electromagnetic signature poses a difficult-to-assess, risk. Thus it is necessary to reduce the levels of electromagnetic signatures, and to quantify the risk. This is the scientific challenge for EM signature management.

Based on this review, it is recommended that emphasis be placed in the following areas in DRDC's EM research program:

Closed-loop degaussing is the frontier of DC magnetic signature control. Much work remains to be able to monitor the near-field magnetism of a vessel and interpret it in terms of the mid and far-field signature. The ultimate goal is a system that renders a naval platform optimally degaussed at all times and all locations world-wide. Here, optimal is defined as the appropriate degree of magnetic signature reduction based on the capability of the expected threat to sense the signature. The determination of optimal signature reduction can only be made on the basis of knowledge of threat systems and simulating their behaviour under the influence of accurately modelled ship signatures.

EM modelling for signature prediction and ship design is important. High-fidelity models of DC electric and magnetic signatures are essential tools for understanding EM signature management. This capability is required for closed-loop degaussing and should be applied at the design stage of future ships in order to achieve optimal degaussing coil arrangements and ICCP electrode placement. EM models are required

to help set signature standards for new ships, investigate signature problems with existing ships and for EM threat engagement modelling.

The current vision for the CF has increased emphasis on deployment abroad and support to forces ashore. This implies a higher level of activity in littoral regions where the threat from EM mines is greatest. The most reliable way to ensure that EM signatures are properly managed is to measure them in theater, a concept known as forward ranging. DRDC Atlantic has already be recognized for its valuable contributions in this area during Operation Apollo. DRDC should enhance activities that contribute to operational forward ranging capability. This also provides a valuable research capability which can be used to study EM signatures at different depths, locations and environmental conditions.

Mine engagement modelling is essential to achieve the goal of minimizing the susceptibility of naval platforms to mines. Engagement modelling combines knowledge of the environment, platform signature and threat characteristics in a simulation that delivers concrete information on mine detonation and the damage it can cause. Only through engagement modelling can the usefulness of EM signature management be understood in the context of actual and future threats. Engagement modelling allows EM signature goals to be determined and tactics to be developed.

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## Annex A: Basic electromagnetism in the oceans

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The broad spectrum of electromagnetic phenomena in maritime environments is more a manifestation of the general complexity of the oceanic system than of the underlying physics. In fact, the science of electromagnetism is mature, having developed quite rapidly in the span of about 100 years starting with Cavendish's experiments in 1771 and culminating in Maxwell's dynamical theory in 1864 [73]. The macroscopic Maxwell equations describe electromagnetic phenomena. In the rationalized MKSA system of units, these are

$$\nabla \cdot \mathbf{D} = \rho, \quad (\text{A.1})$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}, \quad (\text{A.2})$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0, \quad (\text{A.3})$$

$$\nabla \cdot \mathbf{B} = 0. \quad (\text{A.4})$$

In the above set,  $\mathbf{D}$  is the electric displacement,  $\mathbf{H}$  the magnetic field,  $\mathbf{J}$  the current density,  $\mathbf{E}$  the electric field and  $\mathbf{B}$  is the magnetic induction. Constitutive relations,  $\mathbf{D} = \mathbf{D}[\mathbf{E}, \mathbf{B}]$  between the electric field and displacement, and  $\mathbf{H} = \mathbf{H}[\mathbf{E}, \mathbf{B}]$  between the magnetic field and induction supplement the Eqns. A.1-A.4. A generalized Ohm's law  $\mathbf{J} = \mathbf{J}[\mathbf{E}, \mathbf{B}]$  and boundary conditions complete the mathematical description of electromagnetism in macroscopic media.

Whereas, exactly solving the Maxwell equations is attainable for a small number of idealized sources in simple geometries and with stationary boundaries, it becomes intractable for complex or realistic source distributions. It is in this sense that the maritime electromagnetic scenario is complex. The various sources (geomagnetic field, ionospheric couplings, vessels, settlements etc.) and the geometry make general solution of the Maxwell equations for the maritime environment near impossible. Additionally, the electromagnetic coupling due to the motion of the seawater increase the difficulty of the problem. Consequently, with the solution of the general picture beyond reach, individual elements are then tackled separately. The fields from static and alternating electromagnetic sources are treated in Sections A.1 and the inductive effect due to the flow of seawater in a magnetic field is described in Section A.2.

### A.1 Static and alternating electric and magnetic fields

Whereas, electromagnetic signature prediction is sensitive to the details and sophistication of the model, we can illustrate the fundamental physics by solving for the

electric and magnetic fields of an oscillating dipole. The development presented here can be deduced from similar approaches in several books on electromagnetic theory such as reference [73]. For generality, we take an current source  $\mathbf{J}(\mathbf{x}, t)$  surrounded by a source free, infinite, homogeneous, dielectric conducting medium. The magnetic vector potential  $\mathbf{A}$  defined by  $\mathbf{B} = \nabla \times \mathbf{A}$  is the starting point of our solution. Given the magnetic vector potential, the magnetic induction  $\mathbf{B}$  is obtained by simply taking the curl of  $\mathbf{A}$ . The corresponding electric field in the source free space can be found from the Maxwell equation (Eqn. A.2) and constitutive relations for the magnetic field  $\mathbf{H}$  and dielectric displacement  $\mathbf{D}$ . We assume that  $\mathbf{B} = \mu\mathbf{H}$  and  $\mathbf{D} = \epsilon\mathbf{E}$ , where  $\mu$  ( $\epsilon$ ) is the constant magnetic permeability (electrical permittivity). Then we have from Eqn. A.2

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{\nabla \times \mathbf{B}}{\epsilon\mu}. \quad (\text{A.5})$$

For sources oscillating sinusoidally at frequency  $\omega$ , we have  $\mathbf{J}(\mathbf{x}, t) = \mathbf{J}(\mathbf{x})e^{-i\omega t}$  and consequently similar harmonic dependence in the electromagnetic fields. Once the magnetic vector potential can be determined from the current source distribution, the magnetic induction and electric field at any point outside the source is given by

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{E} = \frac{i}{\epsilon\mu\omega} \nabla \times \mathbf{B}. \quad (\text{A.6})$$

The magnetic vector potential in a homogeneous conducting medium is governed by the inhomogeneous wave equation [74, 75]:

$$\nabla^2 \mathbf{A} - \epsilon\mu \frac{\partial^2 \mathbf{A}}{\partial t^2} - \mu\sigma \frac{\partial \mathbf{A}}{\partial t} = -\mu\mathbf{J}. \quad (\text{A.7})$$

The harmonic dependence ( $\mathbf{A}(\mathbf{x}, t) = \mathbf{A}(\mathbf{x})e^{-i\omega t}$ ) leads to rewriting Eqn. A.7 as

$$\nabla^2 \mathbf{A} + \epsilon\mu\omega^2 \left(1 + i \frac{\sigma}{\epsilon\omega}\right) \mathbf{A} = -\mu\mathbf{J}. \quad (\text{A.8})$$

Setting

$$k^2 = \mu\epsilon\omega^2 \left(1 + i \frac{\sigma}{\epsilon\omega}\right), \quad (\text{A.9})$$

identifies Eqn. A.8 as an inhomogeneous wave equation with dispersion relation Eqn. A.9. To solve for the magnetic vector potential, we have to determine the Green function  $G_k(\mathbf{x}; \mathbf{x}')$  that solves the inhomogeneous Helmholtz equation

$$\nabla^2 G_k + k^2 G_k = -\delta(\mathbf{x} - \mathbf{x}'). \quad (\text{A.10})$$

In a boundary free domain, the appropriate Green function is [73, 75]

$$G_k(\mathbf{x}; \mathbf{x}') = \frac{e^{ik|\mathbf{x} - \mathbf{x}'|}}{4\pi|\mathbf{x} - \mathbf{x}'|}. \quad (\text{A.11})$$

It follows that

$$\mathbf{A}(\mathbf{x}) = \frac{\mu}{4\pi} \int d^3x' \mathbf{J}(\mathbf{x}') \frac{e^{ik|\mathbf{x}-\mathbf{x}'|}}{|\mathbf{x}-\mathbf{x}'|}, \quad (\text{A.12})$$

formally solves for the vector potential. Given a source current distribution  $\mathbf{J}$ , one may evaluate the vector potential in Eqn. A.12 and thence the magnetic and electric fields given by Eqn. A.6. To proceed, we restrict the source to be of linear dimension  $d \ll r = |\mathbf{x}|$ . Then, in the far-field it is sufficient to approximate  $|\mathbf{x} - \mathbf{x}'| \approx r - \hat{\mathbf{n}} \cdot \mathbf{x}'$  where  $\hat{\mathbf{n}} = \mathbf{x}/|\mathbf{x}|$ . Expanding the exponential term  $e^{-ik\hat{\mathbf{n}} \cdot \mathbf{x}'}$  in powers of  $k$  in the limit  $kr \rightarrow \infty$  we have (see for e.g. ref [73])

$$\mathbf{A}(\mathbf{x}) = \frac{\mu}{4\pi} \frac{e^{ikr}}{r} \sum_{n=0} \frac{(-ik)^n}{n!} \int d^3x' \mathbf{J}(\mathbf{x}') (\hat{\mathbf{n}} \cdot \mathbf{x}')^n. \quad (\text{A.13})$$

In the above equation, we have dropped the explicit time dependence  $e^{-i\omega t}$ . The  $n = 0$  term corresponds to the contribution from an electric dipole source while the  $n = 1$  term gives the magnetic dipole and electric quadrupole contributions. Higher order terms are significantly smaller. Using only the first term in the expansion in Eqn. A.13 we get

$$\mathbf{A}(\mathbf{x}) = \frac{\mu}{4\pi} \frac{e^{ikr}}{r} \int d^3x' \mathbf{J}(\mathbf{x}') = -\frac{\mu}{4\pi} \frac{e^{ikr}}{r} \int d^3x' \mathbf{x}' (\nabla' \cdot \mathbf{J}(\mathbf{x}')). \quad (\text{A.14})$$

Note that the conservation of charge requires that  $\nabla \cdot \mathbf{J} = i\omega\rho$  where  $\rho$  is the charge density. Substituting for the divergence of the current density in Eqn. A.14 we get

$$\mathbf{A}(\mathbf{x}) = -\frac{\mu}{4\pi} i\omega \mathbf{p} \frac{e^{ikr}}{r}, \quad (\text{A.15})$$

where the electric dipole moment is given by  $\mathbf{p} = \int \mathbf{x}' \rho(\mathbf{x}') d^3x'$ . Having determined the vector potential, the electric and magnetic fields follow from Eqn. A.6:

$$\begin{aligned} \mathbf{B}(\mathbf{x}, t) &= \mathbf{B}(\mathbf{x}) e^{-i\omega t}, & \mathbf{E}(\mathbf{x}, t) &= \mathbf{E}(\mathbf{x}) e^{-i\omega t}, \\ \mathbf{B}(\mathbf{x}) &= \frac{\mu}{4\pi} \omega k \frac{e^{ikr}}{r} \left(1 - \frac{1}{ikr}\right) \hat{\mathbf{n}} \times \mathbf{p}, \end{aligned} \quad (\text{A.16})$$

$$\mathbf{E}(\mathbf{x}) = \frac{k^2 e^{ikr}}{4\pi\epsilon r} [(\hat{\mathbf{n}} \times \mathbf{p}) \times \hat{\mathbf{n}}] + \frac{e^{ikr}}{4\pi\epsilon} \left(\frac{1}{r^3} - \frac{ik}{r^2}\right) [3(\hat{\mathbf{n}} \cdot \mathbf{p}) \hat{\mathbf{n}} - \mathbf{p}]. \quad (\text{A.17})$$

Given real permittivity, permeability and conductivity we have

$$\begin{aligned} k &= \beta + i\frac{\alpha}{2}, \\ \beta &= \sqrt{\frac{\mu\epsilon}{2}} \omega \left[ \sqrt{1 + \frac{\sigma^2}{\epsilon^2 \omega^2}} + 1 \right]^{1/2}, \end{aligned} \quad (\text{A.18})$$

$$\frac{\alpha}{2} = \sqrt{\frac{\mu\epsilon}{2}} \omega \left[ \sqrt{1 + \frac{\sigma^2}{\epsilon^2 \omega^2}} - 1 \right]^{1/2}. \quad (\text{A.19})$$

There are 4 limiting forms to consider with Eqns. A.16, A.17 and A.18, A.19: those in the near and far field, and those for poor and good conductors respectively. The near (far) fields are obtained by applying the  $kr \ll 1$  ( $kr \gg 1$ ) limits to Eqns. A.16 and A.17. In the near zone, we get

$$\mathbf{B}(\mathbf{x}) = \frac{i\mu\omega}{4\pi r^2} \hat{\mathbf{n}} \times \mathbf{p}, \quad (\text{A.20})$$

$$\mathbf{E}(\mathbf{x}) = \frac{1}{4\pi\epsilon r^3} [3(\hat{\mathbf{n}} \cdot \mathbf{p})\hat{\mathbf{n}} - \mathbf{p}]. \quad (\text{A.21})$$

Besides the simple harmonic oscillation, the spatial electric field is that of a static dipole. In the far or radiation zone, we get the expected  $1/r$  radiative decay

$$\mathbf{B}(\mathbf{x}) = \frac{\mu\omega k e^{ikr}}{4\pi r} \hat{\mathbf{n}} \times \mathbf{p}, \quad (\text{A.22})$$

$$\mathbf{E}(\mathbf{x}) = \frac{k^2 e^{ikr}}{4\pi\epsilon r} [3(\hat{\mathbf{n}} \cdot \mathbf{p})\hat{\mathbf{n}} - \mathbf{p}]. \quad (\text{A.23})$$

The poor (good) conductor behaviors are obtained by taking the limit  $\sigma/\epsilon\omega \ll 1$  ( $\sigma/\epsilon\omega \gg 1$ ) in Eqns. A.18 and A.19. For the poor conductor limit we get:

$$\beta \approx \sqrt{\mu\epsilon\omega}, \quad (\text{A.24})$$

$$\frac{\alpha}{2} \approx 0. \quad (\text{A.25})$$

In the good conductor limit we get:

$$\beta \approx \sqrt{\frac{\mu\sigma\omega}{2}}, \quad (\text{A.26})$$

$$\frac{\alpha}{2} \approx \sqrt{\frac{\mu\sigma\omega}{2}}. \quad (\text{A.27})$$

Since the fields are proportional to  $e^{ikr} = e^{i\beta r} e^{-\alpha r/2}$ , their magnitude attenuates with distance. The penetration distance or skin depth  $\delta$  at which the magnitude has decayed to  $1/e$  is given by  $\delta = 2/\alpha$ . For a poor conductor  $\alpha \approx 0$  and so the

magnitude of the electromagnetic fields is approximately unchanged. However, for a good conductor, the magnitude decays exponentially. The penetration distance  $\delta$  is inversely proportional to the square root of both the conductivity and the frequency:

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} = \sqrt{\frac{1}{\pi\mu\sigma f}}. \quad (\text{A.28})$$

For seawater with  $\mu = \mu_0 = 4\pi \times 10^{-7}$ ,  $\sigma \approx 4 \text{ S/m}$ ,  $\delta \approx 250/\sqrt{f}$ . Thus  $\delta = 25 \text{ m}$  at  $f = 10^2 \text{ Hz}$  and only  $0.25 \text{ m}$  at  $f = 10^6 \text{ Hz}$ .

## A.2 Induced fields due to motion of the conducting medium in a magnetic field

A charge moving in a magnetic field feels the Lorentz force perpendicular to both its velocity and the magnetic field. A neutral, conducting fluid such as seawater is comprised of positive and negative ions. When such a fluid is in motion in a magnetic field, the charges are subjected to the Lorentz force which effectively causes opposite charges to move in opposite directions. The subsequent charge separation induces an electric field that counters the Lorentz force. This is the basic mechanism of how the motionally induced electric field appears when seawater flows in the Earth's magnetic field. The induced magnetic field, on the other hand, is a secondary effect due to the electrical current that is maintained by the induced electric field, of course calculated self-consistently. To be fair, the actual system of seawater moving in a magnetic field is very complicated and the foregoing is a gross simplification. Below, we introduce some of the mathematical rigor and clarify the assumptions that are made to obtain a tractable problem.

A fluid or liquid, like water, is largely Newtonian in its response to forces. As such, it is mathematically described by the Navier-Stokes equations for linear compressibility. If the fluid is also electrically conducting or charged, then its physics has to additionally satisfy the Maxwell equations. The fluid behavior is then rather difficult to determine mathematically as the fluid equations are coupled to Maxwell equations through electromagnetic forcing and charge conservation requirements. In certain approximations the physical models of charged and/or conducting fluids are categorized as magnetohydrodynamics, electrohydrodynamics or plasma physics. For large scale, slow flows of oceanic water, it is assumed that the advection of charge by the fluid flow is negligible in comparison to the conduction current [17]. Furthermore, the displacement and polarization currents are similarly small in comparison to the conduction current [17]. Thus, dropping the displacement current in Eqn. A.2, and

assuming the usual constitutive relation  $\mathbf{B} = \mu\mathbf{H}$ , we get

$$\nabla \times \mathbf{B} = \mu\mathbf{J}. \quad (\text{A.29})$$

Since  $\nabla \cdot \nabla \times \mathbf{B} = 0$ , we get  $\nabla \cdot \mathbf{J} = 0$ , which is the conservation of electric current. In a frame moving instantaneously with the seawater at velocity  $\mathbf{v}$ , Ohm's law reads  $\mathbf{J}' = \sigma\mathbf{E}'$ . In the stationary frame,  $\mathbf{J}' = \mathbf{J}$  and  $\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}$ . See for example Ref. [73]. Finally, the induced fields and current density are determined self-consistently from

$$\nabla \cdot \mathbf{J} = \nabla \cdot \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = 0, \quad (\text{A.30})$$

and the appropriate boundary conditions. It is instructive to illustrate a very simple case. In a Cartesian system  $(x, y, z)$  with  $z$  the vertical coordinate, consider the flow  $\mathbf{v} = (u, 0, 0)$  and the magnetic field  $\mathbf{B} = (0, 0, B_z)$  so that  $\mathbf{v} \times \mathbf{B} = -uB_z\hat{\mathbf{y}}$ . Then Eqn. A.30 becomes

$$\nabla \cdot \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = \nabla \cdot (\sigma E_y \hat{\mathbf{y}} - \sigma u B_z \hat{\mathbf{y}}) = 0. \quad (\text{A.31})$$

It follows that

$$\frac{\partial}{\partial y}(\sigma E_y - \sigma u B_z) = 0. \quad (\text{A.32})$$

Taking the velocity, conductivity and magnetic field to be constant, and that the induced field vanishes for zero flow velocity, we get  $E_y = uB_z$ . Thus a flow of 0.1 m/s in a vertical field of 40  $\mu\text{T}$  would lead to an induced electric field of 4 mV/km.

A general solution to Eqn. A.30 for an oceanic geometry is hardly tractable though some attempts have been made [17]. A somewhat successful approximation is to make a ‘‘shallow water’’ approximation and average the field variables over the vertical coordinate. See for example Refs. [12, 20] and references therein. In the vertically averaged approximation, the averaging is weighted by the depth dependent electrical conductivity. The conductivity-weighted averaged flow velocity  $\bar{\mathbf{v}}$  is given by

$$\bar{\mathbf{v}} = \frac{\int_{-H}^0 \sigma \mathbf{v} \, dz}{\int_{-H}^0 \sigma \, dz}, \quad (\text{A.33})$$

where  $H$  is the ocean depth. The resulting  $(x, y)$  induced electric field components [12, 20] are

$$\mathbf{E}_{x,y} = \bar{\mathbf{v}} \times \mathbf{B}. \quad (\text{A.34})$$

Given the difficulty in obtaining exact solutions, the motional induction problem is an area of active scientific research.



## Annex B: Electromagnetic properties of seawater

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There are three properties of the medium that quantitatively determine the electromagnetic fields. These are the magnetic permeability, the electrical conductivity and the dielectric permittivity. Since seawater contains only trace quantities of magnetic elements, its magnetic permeability is essentially that of free space and so has a relative permeability  $\mu_r = 1$  at all frequencies. The ionic content of seawater contributes primarily to the electrical conductivity while the polarizability and the permanent dipole moment of water molecules is largely responsible for the dielectric permittivity.

The dissolved salts in seawater have roughly constant relative abundancies independent of the total salt concentration. Approximately 55% of the ionic mass of seawater is accounted for by the Chloride ion  $\text{Cl}^-$ , with another 30% by the Sodium ion  $\text{Na}^+$ . Sulphate ( $\text{SO}_4^{2-}$ ), Magnesium ( $\text{Mg}^{2+}$ ), Calcium ( $\text{Ca}^{2+}$ ) and Potassium ( $\text{K}^+$ ) account for almost all of the remaining 15% [76].

The salinity,  $S$ , is traditionally defined as the parts per thousand (ppt) of the chloride ion in a kilogram of seawater. Standard seawater has a salinity  $S = 35$ . The electrical conductivity  $\sigma$  is a function of the salinity, the temperature and the pressure. At constant pressure, the conductivity is an increasing function of temperature and salinity. At atmospheric pressure and for standard sea water salinity  $S = 35$  the electrical conductivity  $\sigma(T, S = 35)$  in S/m for the temperature range  $-2^\circ - +35^\circ\text{C}$  is well approximated by [77]

$$\sigma(T, 35) = 2.903602 + 0.08607T + 4.738817 \times 10^{-4}T^2 - 2.991 \times 10^{-6}T^3. \quad (\text{B.1})$$

The salinity dependence is given by

$$\begin{aligned} \sigma(T, S) &= \sigma(T, 35)R_T(S), \quad \text{where} \\ R_T(S) &= R_{15}(S) \left( 1 + \frac{(T - 15)\alpha_0}{T + \alpha_1} \right), \\ R_{15}(S) &= \frac{S(37.5109 + 5.45216S + 0.014409S^2)}{1004.75 + 182283S + S^2}, \\ \alpha_0(S) &= \frac{6.9431 + 3.2841S - 0.099486S^2}{84.85 + 69.024S + S^2}, \\ \alpha_1(S) &= 49.843 - 0.2276S + 0.00198S^2. \end{aligned} \quad (\text{B.2})$$

Equations B.1 and B.2 are suitable approximations for seawater electrical conductivity at shallow depths and for moderate temperature and salinity ranges. Ideally

the temperature should be in the range  $-2^\circ - +35^\circ\text{C}$  and the salinity  $1 < S < 42$ . Typical oceanic seawater conductivities are  $3 - 5 \text{ S/m}$ .

The dielectric properties of electrolytes are described by the Debye relaxation model. Here the complex dielectric permittivity  $K$  is modelled by

$$K = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (i\omega\tau)^\beta} - i \frac{\sigma}{\epsilon_0\omega}. \quad (\text{B.3})$$

In the above equation  $\epsilon_{0,s,\infty}$  are the permittivity of free space, the static dielectric constant and the infinite frequency dielectric constant respectively.  $\sigma$  is the conductivity,  $\omega$  is the frequency,  $\tau$  is the relaxation time and  $\beta$  describes the distribution of times [78]. As with the conductivity, the dielectric parameters of sea water are functions of temperature and salinity. In particular the static dielectric constant is referenced to zero salinity as

$$\epsilon_s(T, S) = \epsilon_s(T, 0)a(T, S). \quad (\text{B.4})$$

Fits of the data to empirical model equations show that [77]

$$\epsilon_s(T, 0) = \frac{37088.6 - 0.82168T}{421.854 + T} \quad (\text{B.5})$$

$$a(T, S) = 1 - \frac{(0.03838S + 0.00218S^2)(79.88 + T)}{(12.01 + S)(52.53 + T)}. \quad (\text{B.6})$$

These empirical fits are adequate in the range  $0 \leq T \leq 25^\circ\text{C}$  and  $2.1 \leq S \leq 38.0$ . Note that at  $S = 0$ ,  $a(T, 0) = 1$  so that the distilled water dielectric constant is recovered. For  $S > 0$ ,  $a(T, S) < 1$  so that increasing salinity at constant temperature lowers the dielectric constant. Similarly increasing the  $T$  at constant salinity also lowers  $\epsilon_s$ . At typical sea water parameters  $T = 15^\circ\text{C}$  and  $S = 35$ , the static dielectric relative permittivity is  $\epsilon_s \approx 72$ .

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The broad field of electromagnetic activity in maritime environments is selectively reviewed from the perspective of scientific signature management. The physical origins and characteristics of naturally occurring electromagnetism *i.e.* ambient electromagnetic fields in the oceans are described. In particular, the sources or physical processes generating the fields, their magnitudes and the relevant time scales are noted. The ambient fields include the Earth's geomagnetic field, electromagnetic fields arising from the Earth-ionosphere coupling and induced fields from oceanic flows. Localized electromagnetic signatures *i.e.* those emanating from naval platforms are reviewed. The signature strengths, their spatial and temporal extent, their origin and the representative physical models are discussed. Platform signatures include electromagnetic effects stemming from corrosion, permanent and induced magnetization of ferromagnetic components, and electromagnetic fields propagating from coastal settlements. Magnetic and electric signature management principles such as degaussing and active shaft grounding, respectively, are described. Defence Research and Development Canada (DRDC) contributions and present-day competencies in electromagnetic signatures are discussed. Possible directions for DRDC electromagnetic signature management are suggested.

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